The History of Spruce Bark Beetle Outbreaks in the Kluane Region as Determined from the Dendrochronology of Selected Forest Stands

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Executive Summary

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Four Kluane forest stands were sampled during June 2001, and two major spruce bark beetle infestations were detected. A widespread outbreak, first detected in the Kluane region during 1994, has killed mature white spruce trees in each of these forest stands. In addition, the Papineau Road forest stand showed evidence of a beetle infestation that began in 1934 and continued to 1942. According to Downing (1957), this outbreak was part of an infestation that extended from approximately the BC-Alaska border to near the village of Champagne on the Alaska Highway. Coring trees near Klukshu, Rod Garbutt and co-workers from the Canadian Forestry Service have found evidence of the 1934-42 outbreak. Sampling additional trees from this area could document the extent of this 1930-40s beetle infestation.

Other than these two outbreaks, the four forest stands sampled show no major spruce bark beetle activity in the history of these stands. Rod Garbutt has cored and measured a small number of mature white spruce trees from five other sites in the Kluane region, and these trees offer no evidence of other widespread beetle outbreaks. By comparison, similar studies carried out on the Kenai Peninsula have documented five major beetle outbreaks, three during the 20th century and two during the 19th century. These results suggest that there are significant differences in the dynamics of the spruce bark beetle in the Kluane forests as compared to the Kenai forests.

The two documented infestations in the Kluane region (beginning approximately 1934 and 1994) appear to be 20th century phenomena, probably linked to the series of drier, warmer summers and milder winters that became increasingly evident as the century progressed. During the 1990s, the series of warm, dry summers and mild winters increased the spread of the bark beetles across the Kluane region. However, if the future climate of the Kluane region continues to become warmer and drier, the white spruce trees of the region might experience two effects: (1) increased moisture stress, and (2) greater mortality from the increased production of spruce bark beetles. A combination of not only more susceptible trees but, more importantly, enhanced beetle populations from warmer summers may lead to increased attack and mortality of smaller size classes of trees, such as has been observed on the Kenai Peninsula in the 1990s.

The lack of any significant tree growth ring pulses (caused by spruce bark beetle outbreaks) previous to 1930 suggests that widespread, severe beetle infestations are rare events in the forests of the Kluane region. Based on the forest stands sampled, we conclude that widespread, intense spruce bark beetle outbreaks have been rare occurrences in the forests of Kluane for a period extending from the early 1300s (the start of the Little Ice Age) until the early 1930s. Additional sampling of white spruce trees on other sites in the Kluane region would further test this hypothesis.

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Introduction

Spruce Bark Beetle

The spruce bark beetle (*Dendroctonus rufipennis* Kirby) is the most significant insect agent of mortality of spruce forests in both the northern latitudes of North America and the high altitudes of the Rocky Mountains (Ford 1986). In the Kluane area the only host tree supporting the spruce bark beetle is the white spruce *(Picea glauca*). In other areas of western North America, Sitka spruce (*P. sitchensis*), the white-Sitka spruce hybrid Lutz spruce (*Picea* X *Lutzii*), and Engelmann spruce (*P. engelmannii*) are commonly attacked by this insect. In addition, black spruce (*P. mariana*) and blue spruce (*P. pungens*) are infrequently attacked.

Spruce bark beetle attacks have occurred in many places in western North America for decades. Ford (1986) describes a typical attack:

> While epidemics of the beetle populations have destroyed spruce over large areas, latent beetle populations normally colonize windthrown or moribund trees. Outbreaks generally start in unmanaged mature forests when beetle populations build up in windthrown patches or logging slash, and invade living trees when their favored downed material is exhausted. Traditionally, spruce beetle outbreaks have been managed only after substantial numbers of trees have been killed.

However, patterns of beetle attacks are changing. Currently southern Alaska and southwestern Yukon Territory are experiencing a regional outbreak of spruce bark beetle that has killed many mature spruce trees over a large area. Since 1989, when the current infestation of beetles accelerated, 2 to 3 million acres (0.8 to 1.2 million ha) of spruce forest on the Kenai Peninsula have experienced an outbreak of beetles (Berg 1998; Fastie et al., 2000). In this region, a majority of the mature white and Sitka/Lutz spruce trees has been killed by beetles. This widespread death of mature trees has thinned forest canopies and released growth in surviving understory trees.

Large-scale outbreaks of spruce bark beetles have occurred on the Kenai Peninsula during the last 250 years. Berg and co-workers used dendrochronology to identify previous periods of canopy thinning in 23 widely distributed stands in the Kenai Peninsula-Cook Inlet area. They found tree-ring evidence of regional spruce bark beetle outbreaks in the 1810s to 1820s, 1870s to 1880s, 1910s, and 1970s (Berg 1998, 1999; Berg and De Volder, 1999; Fastie et al., 2000).

The current regional outbreak of spruce bark beetles has also been extended northward and eastward and has affected large areas in the Wrangell-St. Elias National Park and Preserve of south-central Alaska. Starting in 1989, an outbreak of spruce bark beetle has resulted in mortality of mature white spruce on nearly 250 000 ha in the Copper River Basin — 100 000 ha of which occur within the boundaries of the national park and preserve (Wesser and Allen 2000).

In the Kluane region, Rod Garbutt of the Canadian Forest Service has conducted annual “red needle” survey flights and has documented recent beetle activity. Garbutt (2000, pers. comm.) states that the spruce beetle infestation in southwest Yukon currently has affected an area in excess of 250 000 ha. Approximately half of the infested area lies in the Shakwak Trench between Kluane Lake in the north and the upper Tatshenshini River in the south. The other half is contained within the Alsek River drainage, inside the borders of Kluane National Park and Reserve. Evidence suggests that the outbreak began in the region during the early 1990s, but it was not detected until it had spread into the Shakwak Valley during 1994. By then it was already 32 000 ha in size. By 1999 many mature white spruce trees were dead in the Alsek River Valley, adjacent sections of the Tatshenshini, and the Shakwak Trench between Kluane Lake and Dezadeash Lake. By 2001 the infestation had largely subsided due to a lack of susceptible host trees, but a remnant population of beetles survives in the scattered remaining live spruce. However, during the dry summer of 2002, Garbutt (pers. comm.) mapped recently beetle-killed white spruce trees over 69 415 ha which was a threefold increase over the previous year. In Kluane National Park and Reserve, younger spruce trees were succumbing to bark beetle during the dry summer of 2002, but this pattern was not observed on the eastern half of the Shakwak Trench. At this point, it is not possible to predict if the beetles will spread into new areas east of the Shakwak Trench.

Garbutt (2000, pers. comm.) is not able to predict how long the infestation will last. He observes that it has already outlasted all of the historic spruce bark beetle attacks that have occurred in British Columbia, infestations that usually peaked after a duration of three or four years and then quickly subsided (see also Ford 1986; Hard 1985, 1987). Garbutt predicts that the pattern and duration of vegetative changes resulting from the beetle attacks will largely be determined by the abundance and vigor of the white spruce understory (see also Wesser and Allen 2000). In stands with a well-stocked understory, young trees will respond to reduced competition for light, moisture and nutrients, and the transition will likely be rapid and smooth. In other less well-stocked stands, new openings will persist and will likely be colonized by woody shrubs such as *Shepherdia, Betula* or *Salix* species. Garbutt and co-workers have established permanent transects to monitor the vegetation changes resulting from this beetle infestation. The Kluane Ecological Monitoring Project is also documenting patterns of change in plant and animal populations of Kluane's spruce forests (see Krebs et al., 2002).

Dendroctonus rufipennis is probably endemic in the Kluane region. Traditional knowledge from the Southern Tutchone has terms and uses for the larvae of the spruce bark beetle (Gaunt, pers. comm.), suggesting that the spruce bark beetle has existed in the Kluane region for perhaps centuries. Historic accounts of outbreaks of the spruce bark beetle exist for the Kluane area (e.g., Downing 1957, discussed below).

Little information exists concerning the frequency and extent of *Dendroctonus rufipennis* attacks in the Kluane region during past centuries. It is the purpose of this research project to examine the frequency of past spruce bark beetle attacks in selected forest stands of the Kluane region using well-established methods of dendrochronology.

Tree Ring Evidence of Past Beetle Attacks

Evidence for past outbreaks of *Dendroctonus rufipennis* can be found in growth pulses of trees that survived beetle attack. This accelerated growth of the surviving trees represents a release from competition, due to death of surrounding larger trees and the resultant thinning of the forest canopy. Spruce bark beetles selectively attack mature spruce trees, because large trees are less able to resist the establishment of adult female beetles in the inner bark (phloem) layer. After attack, the smaller surviving trees receive more light, soil moisture and nutrients, and their diameter growth often increases abruptly and dramatically. A dendrochronological method based on this growth pulse in trees was used by Veblen et al. (1991 a, b) to study bark beetle outbreaks in Englemann spruce in Colorado during the 1850s and 1940s, and Berg's research team has used a similar method to study past spruce bark beetle attacks on the Kenai Peninsula in Alaska.

These dendrochronological methods rest on the premise that significant growth releases in understory spruce trees (as evidenced by larger growth rings) are best explained as a result of past attacks by *Dendroctonus rufipennis.* Analyses show that when understory trees survive the disturbance and show significant release in their growth rates, outbreaks of the spruce bark beetle appear to be the most feasible forest-thinning agent. No other forest insect or tree disease of southern Alaska or southern Yukon is known to preferentially kill mature spruce trees and create accelerated growth in the understory trees (Holsten et al. 2001).

Forest fires will only infrequently create these patterns. Fires in spruce stands are usually stand-replacing events, and typically forest fires do not favor the survival of understory trees (Rowe and Scotter 1983; Veblen et al. 1991 a, b). Windstorms can effectively act as a thinning agent, but windstorms in the Kluane region blow down mature trees on a sporadic or localized basis. Regional destruction of mature trees by windstorm (e.g., hurricane-scale storms, see Henry and Swan 1974) has not been documented to occur in the Kenai region of Alaska (Berg 1998; Berg and De Volder 1999) nor in the Kluane region (Environment Canada, Parks 1987). Selective cutting by humans can preferentially remove large trees and cause a release in understory trees, a method often used by foresters to promote increased timber volume in a stand. There were, however, no cut stumps in any of the stands that we sampled. Thus in regions where large, mature spruce trees are selectively killed with the resultant opening of the canopy and released growth in the understory spruce trees, the most probable disturbance agent appears to be an infestation of *Dendroctonus rufipennis*.

Methods

Description of the study area and site locations. Kluane National Park and Reserve lies in the southwestern corner of the Yukon Territory, a large montane area containing some of the largest non-polar ice caps and valley glaciers in existence. Kluane National Park and Reserve is 22 015 km^2 in size. Approximately 18 percent of it is vegetated, largely a narrow "green belt" area associated with the Shakwak Trench, Duke Depression and parts of the Kluane Range. Ecologically these are the most productive lands of the park, and parts of the Shakwak Trench (both inside and outside the park), Alsek River valley and parts of the Tatshenshini – Alsek Park in northwestern British Columbia contain areas where the recent spruce bark beetle infestation has been most intense (Garbutt 2000). The climate, geology, vegetation, and ecology of Kluane National Park and Reserve are described by Environment Canada, Parks (1987). The four main study areas selected for this project were all located in the Shakwak Trench (see Fig. 1). Criteria for the selection of these four study sites are explained later in this section.

Increment cores. We took tree increment core samples with increment borers at waist height (100-120 cm) above the ground, during the week of June 25-29, 2001. Four stands were sampled (see Fig. 1), for a total of 421 increment cores and 18 cross-sections of burnt, dead trees (the latter samples are referred to as "cookies"). Most increment cores were taken from live trees, although old dead snags were sampled whenever possible. We preferentially sampled the oldest-appearing trees (usually the largest) to get the longest possible record of stand history. We further required that sampled trees be at least 10 meters apart, so as to avoid duplicate samples from trees whose growth might be responding to the death of a single overstory tree. Cross-section samples were taken from burnt poles to date the origin of fires prior to and within the lifetimes of the stands (see Appendix B). Hawkes (1983) and Francis (1996) suggest that most of the forests in the Kluane region originated as post-fire forests.

The core samples were oven-dried and glued onto wood mounts for stability and ease of handling, and then sanded with progressively finer sandpaper to 600# grit. Ring-widths were measured to an accuracy of 0.01 millimeter with a Velmex sliding bench micrometer, using a binocular microscope of 20-60x power. The set of ring-width measurements for each core (called a "series") was compared with the mean ring-widths for all series to check for errors and consistency of dating, using the software COFECHA, developed by the Laboratory of Tree-Ring Research at the University of Arizona-Tucson (Holmes et al. 1986). These methods are standard procedures of dendrochronology (Stokes and Smiley 1968). Graphs of the ring-width measurements for the older trees are presented in Figs. 2, 4, 6, and 8.

Cross-dating and death dates. Once the dating of each ring of each series has been confirmed, COFECHA determines the date of the outermost ring of each series (called the "death date" of the tree, if this is the last ring under the bark) by comparing the ring-widths with the average ring-widths of all the series, year by year. This process is called "cross-dating" and is essential for dating dead wood of any kind. Further details of these methods are provided in Appendix B.

Growth releases. In this study the concept of "growth release" is critical, and we make this concept precise by operationally defining a *release* as a doubling of the mean ring-width over a ten-year period. That is, for each year we calculate the mean of the next (forward) ten rings, and the mean of the past (backward) ten rings, and ask if the ratio of the forward mean to the backward mean has doubled (i.e., the ratio exceeds 2.0). We make this calculation for each tree, using the computer-based program JOLTS, written by Richard Holmes of the Laboratory of Tree-Ring Research.

For each stand, we summarize growth releases detected by JOLTS on a graph that shows the release history of each sampled tree (Figs. 3, 5, 7, and 9). Each horizontal line in the graph represents the lifespan of a single tree, as seen in an increment core along a single radius. Releases are plotted as black vertical bars, and the series are arbitrarily arranged from the oldest tree to the youngest tree found in the stand. The graphics software FHX2 is used to prepare these graphs (Grissino-Mayer 2000).

Growth releases can be visually determined, but the computerized JOLTS procedure makes the scoring of releases completely objective, once the tree-rings have been measured.

To summarize the growth patterns of forest stands on a regional scale we prepared a graph showing the percentage of trees growing at *twice* the overall growth rate (i.e., with ring-widths > 2x the stand average), comparing the four Kluane stands with twenty stands in the Kenai Peninsula – Cook Inlet area (Fig. 10A). This graph shows the duration of periods of rapid growth, whereas the JOLTS graphics (Figs. 3, 5, 7, 9) emphasize the onset of rapid growth, i.e., the "moment" of release rather than the duration of release.

We prepared a similar, more detailed graph of the four Kluane stands for the period 1970-2000 to see if any slight acceleration of growth could be detected in response to the 1990s beetle outbreaks (Fig. 10B). In order to detect a slight acceleration of growth, in Fig. 10B we used a weaker concept of release – that is, the growth rate merely exceeded the mean (i.e., 1x, rather than 2x of the stand mean).

Release Probabilities. The JOLTS graphics (Figs. 3, 5, 7, 9) examine growth releases over the lifetime of the stand. It is also useful to calculate an overall probability of release in a stand and to compare this statistic with other stands. Specifically we ask: what is the probability that a given tree-ring in a given tree will shift to the released condition (i.e., that the ten-year ring-width mean will have doubled)? We can estimate this probability for an entire stand by calculating the frequency of release in a sample of several thousand rings measured in the increment cores from that stand. To calculate this frequency we count the number of observed releases and divide by the total number of possible rings (years) that could have shown a release. For example, in the 128 cores and cookies from Papineau Road we observed 103 releases in 18 392 measured rings, so the estimate of the release probability is 0.0056 = 103/18 392, or 5.6 trees per thousand per year.

One can interpret this calculation in various ways: as the observed proportion or frequency of releases in all available tree-years; as an estimate of the probability of observing a release in any given tree in any given year; or as an estimate of the number of trees per thousand that could be expected to show a release in any given year. It is important, however, to keep in mind that release events are typically clustered in a few years, especially when bark beetles have created substantial mortality. In these cases an expected yearly release rate does not mean much, because most years will experience no release events. The release probabilities for the four Kluane stands are compared to various Kenai stands in Fig. 11. Species with little of no susceptibility to spruce bark beetles (black spruce, hemlock, and birch) are also included in Fig. 11 for comparison.

Radial growth rates. We can take the average ring-width in a stand as an estimate of the radial growth rate of the trees. (This ignores bark thickness, which increases very slowly from year to year.) To make this calculation we simply average all the measured ring-widths for a stand. This includes years of suppressed growth, as well as initial vigorous growth in post-disturbance stands and accelerated growth during release events. We calculate the standard deviation to express the amount of variation in the widths of the growth rings. Growth rates for the four Kluane stands are compared to various forest stands in the Kenai Peninsula – Cook Inlet area in Figure 12.

Forest Stands Sampled in the Kluane Region. We sampled four mature spruce stands, taking 70 to 128 cores and cookies per stand. These forest stands were selected based on the following criteria:

(1) Maturity: the stands contained a substantial proportion of old living trees that were likely to yield rot-free increment cores of several hundred years duration. This required that the sites be above the 17th and 18th century levels of Neoglacial Lake Alsek (Reyes and Smith 2001).
(2) The stands showed at least a low level of current spruce bark beetle activity. The presence of current infestation would suggest that there is nothing peculiar about the site that would mitigate against spruce bark beetle infestation, such as soils or weather patterns.
(3) The stands had less than 20% hardwoods. The presence of a high proportion of a non-beetle susceptible tree species will dilute the thinning effect of white spruce mortality on the surviving white spruce.

In total, we were able to select four stands that met the above criteria. Three of the four stands had beetle monitoring transects established by the Canadian Forest Service in 2000 (Rod Garbutt, project leader) which provided additional information about these stands. The four stands are described as follows:

Papineau Road (Elevation: 759 m. GPS location using WGS84 as the map datum: the area sampled began at the point E 386975, N 6690873 and moved westward). The Papineau Road stand was selected because of the existence of a US Forest Service report (Downing 1957) concerning a 1940's outbreak of spruce bark beetle partly along the Haines Road near Papineau Road (see Appendix A). This stand was selected to provide a case where tree growth response could be measured against a documented historical outbreak. The forest stand sampled was located west of the Haines Road and 1.6 km south of the junction with Papineau Road. This mesic forest stand is a mature white spruce forest in part occurring on a steep east-facing slope. The toe of the slope and ridge top were also sampled. The stand contained many dead white spruce trees, both standing and fallen, and fire sign was present in the stand. In total, 128 cores and cookies were collected at this site. Common shrubs found in this stand included buffaloberry (*Shepherdia canadensis*), rose (*Rosa acicularis*), alder (*Alnus crispa*). Ground cover was partially composed of arctic lupine (*Lupinus arcticus*), arnica (*Arnica* spp.), fireweed (*Epilobium angustifolium*) and bunchberry (*Cornus canadensis*).

Airport Road (Elevation: 667 m. GPS location using WGS84 as the map datum: the area sampled began at the point E 362332, N 6741122 and moved northward and eastward). The forest stand sampled was located east of the road to the Haines Junction Airport and adjacent to Rod Garbutt's Plot #5. There is a clearing 75 m east of the road. Both the clearing and down trees next to the road showed signs of burning. Abundant old, down trees occur in this mesic stand. The closed canopy stand was dominated by white spruce with scattered aspen. In total, 110 white spruce trees were increment cored in this stand.

Burnt poles were not found within this stand; thus, no cookies were collected. Shrubs were not common in this stand. The ground cover was partially composed of fireweed, feather mosses and coarse woody debris. In addition, approximately 20 white spruce trees west of the Airport Road were also increment cored. The stand west of the road was similar to the stand east of the road, but it was hygric with shallow, standing water covering certain areas. Fragments of old burned stumps were visible within the stand, but we found no pieces of burned wood solid enough to use for tree-ring dating,

Marshall Creek (Elevation: 780 m. GPS location using NAD 27 as the map datum: the area sampled began at a point E 372524, N 6748246 and moved northward and westward). This mesic forest stand was located on the benchlands west of Marshall Creek. The forest is a fairly closed canopy stand with large white spruce trees well represented in the stand. In total, 119 cores and cookies were collected at this site. Common shrubs growing in the stand included rose and dwarf birch (*Betula* spp.). Ground cover was partially made up of bunchberry, dry ground cranberry (*Vaccinium vitis-idaea*) and feather mosses. Trees sampled in this stand were within approximately 100 m of Rod Garbutt's Plot #1 transect. Cut stumps were absent from this stand although the stand was located within 0.5 km of a recent clear-cut area.

Ten Km South on the Haines Road (Elevation: 796 m. GPS location using NAD 27 as the map datum: the area sampled began at the point E 368288, N 6732989 and moved eastward). Two forest stands were sampled on the east side of the Haines Road approximately 10 km south of the center of Haines Junction. One stand was located adjacent to Rod Garbutt's Plot #19 transect. The other stand was also on the east side of the road, located approximately 1 km north of the first. Both stands were in mesic white spruce forest containing a minor component of aspen and balsam poplar. The canopy dominated by mature white spruce was semi-open, and recently dead white spruce and aspen, standing or lying on the forest floor, were present in the stand. Understory white spruce trees were numerous. In total, 70 cores and cookies were collected at this site. Common shrubs included dwarf birch and willows (*Salix* spp.). Ground cover was mostly composed of dry ground cranberry, crowberry (*Empetrum nigrum*), arctic lupine, graminoids, Peltigera lichen and feather mosses.

Neoglacial Lake Alsek. The four forest stands selected for sampling were all located above the high water mark of Neoglacial Lake Alsek. Reyes and Smith (2001) successfully crossdated six driftwood samples providing new constraining dates for the three recent phases of Neoglacial Lake Alsek. The last major lake phase ended sometime between 1857 and 1891. Earlier, more extensive lake phases ended between 1788 and 1832, and sometime after 1611. The crossdated driftwood from beaches associated with the three separate phases of Neoglacial Lake Alsek corresponded to elevation levels of 595, 623 and 640 m as reported by Clague and Rampton (1982). Reyes and Smith's data (2001) suggest that the high water mark of Neoglacial Lake Alsek was reached and the Lowell Glacier retreated from its maximum Little Ice Age position sometime shortly after 1611. The elevations of the four stands sampled during this study indicate that they were located between 27 m and 156 m above what is believed to be the high water mark of the lake (Reyes and Smith 2001).

Sample Selection. We do not consider our sample of stands to be a random sample of mature white spruce stands in the Kluane area. The Papineau Road stand was specifically chosen because of the documented history of 1940s beetle-kill in the area. The Haines Road site and Airport Road site were chosen near major roads, where construction-generated slash could have created beetle outbreaks. Other than these considerations, we would argue that the four forest stands appear to be representative of Kluane's white spruce stands on productive sites in the valley-bottom lands of the Shakwak Trench. These are some of the most common and productive forests found in the region (Environment Canada, Parks 1987).

Results

Age, Growth Rates and Release Patterns in the Four Stands

Each of the four forest stands were analyzed separately concerning stand origin, age of trees making up the stand, growth rates, and patterns of significant releases in growth rates.

Papineau Road

The Papineau Road stand is the "control group" in this study, because of the historical report of a spruce bark beetle outbreak along the Haines Road in the early 1940s (Downing 1957). We cored both standing and down bark beetle scarred trees and obtained tree-ring estimates of death dates ranging from 1934 to 1942 (see Appendix B). As expected, the surviving trees exhibited strong releases and indeed many today are still growing at more than twice the average growth rate for the stand (Figs. 4, 5, 10A). The Haines Road was constructed along the Dalton Trail during World War II (Environment Canada, Parks 1987). The death dates of the beetle-scarred trees clearly indicate that beetle infestation was present in the stand 6-8 years before the construction of the Haines Road began. It is entirely possible that construction-generated slash intensified the infestation by providing fresh horizontal trees, which are the most favored beetle habitat (Hard 1985, 1987).

Burn poles provided evidence for two fires during the lifetime of the present stand in 1758 and 1850 (see Appendix B). The 1758 and 1850 fires generated 10 and 8 statistically significant releases, respectively, during the decade following each of these fires (Fig. 4). Only 20 trees from this sample predated and survived the 1758 fire. Ten of these trees showed a release after the fire and became dominant trees in this forest stand. By comparison, 99 trees predated and survived the 1850 fire, and only 8 trees showed a significant release in growth. These patterns suggest that the 1850 fire was not intense and did not initiate a stand-replacing event.

Airport Road (Garbutt's Plot #5)

The oldest tree in this stand was a meter-high sapling in 1756, and it was still alive in 2001. Fig. 7 indicates that trees established continuously from 1756 to 1850, and their rapid early growth suggests post-fire recruitment (Figs. 6, 10A). There was abundant old, burned wood in the stand, but we found no burnt trees suitable for cross-dating. The tree ages suggest a 1750s fire (see Appendix B). The pattern of releases shows no evidence of systematic thinning having occurred during the history of this stand (Fig. 7).

The average age of the trees sampled was 182 $\pm$ 28 years. The oldest tree sampled was 245 years, and the youngest tree sampled was 132 years of age. The annual radial growth rates in the trees that we sampled in this stand varied at least by a factor of 30. A young tree growing between 1804 and 1834 exhibited an average growth rate of 2.12 mm per year. On the other hand, mature trees growing between 1966 and 1996 showed suppressed growth, averaging 0.3 mm per year. The average growth rate of the sampled trees was 0.66 mm per year, with a standard deviation of 0.4 mm per year (Fig. 12).

Rod Garbutt's 2000 survey data showed 52% of the trees were healthy; 2% had current beetle infestation; 3% were in the red-needle condition, and 42% were dead.

Marshall Creek (Garbutt's Plot #1)

The stand on the benchlands above Marshall Creek was the youngest forest sampled in this study, and it also exhibited the highest average growth rate. The two oldest standing trees sampled were meter-high saplings in 1796 and 1797, and both of these trees died when they were 200 years old. Trees established themselves in the stand on a continuous basis since 1796, giving no evidence of a stand-wide disturbance event occurring in this forest during the past 200 years.

Two samples of burned wood were collected; one cross-dated satisfactorily to 1750, and the other rather poorly to 1777 (and should probably be discarded). The rapid early growth of the trees indicates that this is a post-fire stand, following a mid-1700s burn.

This forest shows an average growth rate of 1.05 mm per year, with a standard deviation of 0.6 mm per year. This is the largest average growth rate of the four forest stands analyzed in this project.

Fig. 9 shows that releases have been infrequent. A small percentage of the trees show a significant release between 1985 and 1990, and these releases combine with approximately eight trees dying during or slightly before this period. In the 1989-95 there was a slight temporary increase in mean ring-width (to 0.6-0.8 mm/yr), and the proportion of trees growing at greater than average rate increased to approximately 20% (Fig. 10B). Taken together, these facts may be the first indicators of spruce bark beetle activity in this forest**.**

Rod Garbutt's 2000 survey data showed 67% of the trees were healthy; 13% had current beetle infestation, and 20% were dead.

Ten Km South on the Haines Road (Garbutt's Plot #19)

This stand contained the oldest tree that we sampled, that is, a tree at least 433 years of age. This tree was a sapling in 1538 and died in 1971. Another tree in the stand was at least 424 years old, living between 1577 and still alive in 2001. Between 1624 and 1674, 31 different trees established and exhibited rapid early growth that is typical of a post-fire stand (Fig. 2).

The average radial growth rate of the trees sampled in this stand is calculated to be 0.48 mm per year with a standard deviation of 0.24 mm per year (Fig. 12). Thus on average a tree in this stand is putting on 0.96 mm of new wood each year. Growth rates varied considerably. One tree that was a sapling in 1634, over the next 30 years averaged growth rings of 1.44 mm per year. Older trees often grew considerably slower. Between 1970 and 2000, one tree showed growth rings that averaged 0.11mm per year.

Fig. 3 shows that there is no pattern of release events during the growth history of this stand. The burn pole cookies (Fig. 2: 14EB, 05EB, 16EB, 08EB, 15DH, 13EB, 09EB, 12EB6271) show clear evidence of a 1721 fire in at least part of the stand. However, there was no significant thinning response regarding released growth rates to this fire, nor to any other kind of thinning event such as a bark beetle infestation (see Fig. 3 and Appendix B).

Rod Garbutt's 2000 survey data showed 45% of the trees were healthy; 18% had current beetle infestation, and 37% were dead.

Supplementary samples

Rod Garbutt measured the ring-widths of a small subset of 28 older cores taken at his sites surveyed in 2000: Marshall Creek (1 core), Klukshu (10), Airport Road (5), Congdon (5), Aishik (1), Dezadeash (2), and south of Haines Junction (4). The sample sizes were too small for statistical significance, but three of the sites showed releases in the 1930s and 1940s, in the same time period as the documented Papineau Road beetle outbreak. The three sites and release dates (1 core unless noted otherwise) are: Klukshu (1935 [2 cores], 1936 [2 cores], 1938, 1939, 1941, 1948), Congdon (1933, 1940, 1948), and Dezadeash (1942, 1946). No other periods of release were noticeable in this small collection of samples.

Discussion

Tree Growth in the Kluane Region

This study allows an examination of the rates of tree growth for white spruce on productive sites in the Kluane region. Average growth rates for the four forest stands sampled are calculated to be: Ten Km site is 0.44 mm/yr; Marshall Creek site is 1.05 mm/yr; Papineau Road site is 0.75 mm/yr; Airport Road site is 0.65 mm/yr. These data suggest that white spruce trees on productive sites in the Kluane region are generally growing at less than 1.0 mm/yr. This average growth rate is fairly low. Spruce trees in southern British Columbia, for example, grow on average at twice or, in some places, three-times Kluane's average growth rate (Canadian Forest Service, unpublished data).

What are the implications of these slow growth rates in the Kluane region? From a forestry point of view, it means a very long rotation interval. A white spruce tree that is 12 inches (30.5 cm) DBH is probably still not large enough to be of value to saw log operations; yet based on the 439 white spruce trees that were measured in this study it will take an average of 150 years or longer to produce that tree. Figure 12 compares the average growth rates in Kluane forest stands to those on the Kenai Peninsula. Three of the four Kluane white spruce stands are growing slower than all but one of Kenai white/Lutz/Sitka spruce stands. White spruce trees on productive sites in Kluane are growing at rates similar to trees at treeline on the Kenai Peninsula.

Should these slow growth rates influence forest and land use planning? If a white spruce forest is harvested in the Kluane region, it will be 150 to 300 years before a medium-sized white spruce forest will be growing on that site again. These slow growth rates could also have impacts on prescribed burning programs. Slow growth rates will probably not influence a fuel reduction program, but if the intent of a prescribed burn is to encourage the regeneration of certain tree species, slow growth rates and a lack of seed sources are important factors to consider. In areas of the Kenai Peninsula where there is 100% beetle kill of spruce, prescribed burning will result in very little spruce regeneration because there are no remaining seed trees.

For post-fire spruce regeneration, it is important to evaluate seed sources when planning a prescribed burn. In the Kluane area, the soil could be bare for quite a while if there are no seed trees close at hand. What shrub or herb species might vegetate these sites? What erosional problems might occur? These plant dynamics should be addressed before a prescribed burning program is carried out.

Evidence of Past Spruce Bark Beetle Outbreaks in the Kluane Forests

As we have discussed, growth pulses in rings of trees that survived previous beetle attack are the chief evidence for past outbreaks of spruce bark beetles. When many decades have passed since the outbreak and the beetle-killed trees have rotted away (in the Kluane region this may take centuries), the annual tree-rings preserve a remarkable record of the forest thinning and the response of individual trees to this disturbance. This visible growth release among the surviving trees in response to *Dendroctonus* spp. attack has been found by Veblen et al. (1991 a, b) in Engelmann spruce in Colorado and by Berg and co-workers in white, Sitka and Lutz spruce on the Kenai Peninsula in Alaska (Berg 1998, 1999; Berg and De Volder, 1999).

How do the four forest stands that we examined in the Kluane region compare to these patterns? The Papineau Road stand presents a clear picture. In this forest, many mature white spruce trees were killed by spruce bark beetles during a beetle outbreak that began about 1934 and continued into the mid-1940s. Dead standing and down trees showed clear evidence of maternal galleries from spruce bark beetle females, and these trees are numerous in this stand. We death-dated these trees, and they died in the late 1930s and early 1940s. The surviving trees showed a pronounced growth release after the beetle attack, and many of these trees continue to exhibit this growth pulse today because the forest canopy has not reclosed. The tree rings sampled in this stand present a pattern quite similar to the forest stands studied on the Kenai Peninsula (Figs. 10A-B).

On the Kenai Peninsula, releases typically last for 60-80 years (Fig. 10A). That is, when a stand is thinned by a beetle attack, the surviving trees are released and grow faster for 60-80 years. These survivors are typically skinny poles in the understory at the time of attack. Some new stems also get established, but it is the former understory trees that show the 60-80 year growth pulse as they reach into the opened canopy. At Papineau Road, the growth pulse from the late 1930s is still visible. Many of the trees are still growing quite vigorously, although growth has slowed in many trees since 1998 (Fig.10B). In Kluane the amount of time for the canopy to close and the trees to return to a suppressed growth rate may be longer than 60-80 years because of the generally slow growth rate of the trees.

We only have one stand (Papineau Road) that shows any evidence of past spruce bark beetle outbreaks. Our other three Kluane forest stands (Ten Km, Marshall Creek and Airport Road) show no evidence of stand-wide release events in the history of these stands. In these three stands, there was evidence of only scattered releases, the number expected in a typical forest stand from individual trees dropping out and neighboring trees showing a release. On the Kenai, we see this pattern in black spruce and hemlock stands that are not appreciably attacked by insects such as the spruce bark beetle.

In summary, prior to 1990 three of the four stands sampled show no evidence of having been attacked in a major way by spruce bark beetles since these stands originated. The Ten Km stand originated in the mid-1500s; the Airport Road stand originated in the mid-1700s, and the Marshall Creek stand originated in the late-1700s. If we assume that the four sampled stands are representative samples of the Kluane region (and we believe that this is a fair assumption), then the fact that only one of the four stands shows previous beetle-kill suggests that spruce bark beetle outbreaks have been rare occurrences in the forests of the Kluane region during the past several centuries. Furthermore, as noted, Rod Garbutt and co-workers from the Canadian Forest Service have examined 28 cores from mature white spruce from 7 different sites in the Kluane region. This is admittedly a small sample size. However, the lack of synchronized releases among the growth rings of these trees (other than during the documented 1930-40s outbreak on the Haines Road) offers some additional evidence that spruce bark beetles outbreaks in Kluane forests were small in extent and infrequent in occurrence during the past several centuries.

Release Probabilities

Every white, Lutz, or Sitka spruce stand that we have examined in the Kenai Peninsula – Cook Inlet area shows at least one, and sometimes as many as five, statistically significant growth pulses (Fig. 10A). This abundance of releases creates substantial release probabilities of 0.005 to 0.020, or 5 to 20 trees per thousand per year (Fig. 11). Papineau Road with its 1930-40s release fits into the low end of the Kenai pattern with a rate of 0.0057, or about 6 trees per thousand. The other three Kluane sites, however, show extremely low rates, around 1 tree per thousand, comparable with black spruce on the Kenai. This pattern shows that these three stands have been remarkably stable and undisturbed during the 200 to 400 years recorded in their rings, even though one of the stands – Ten Km – showed evidence of a 1721 fire during the lifetime of the stand.

Spruce Bark Beetle Outbreaks and Forest Fire Hazards

There is public concern in the Kluane region that the present spruce bark beetle outbreak with its numerous dead mature spruce trees will greatly increase the risk of forest fires in this region. The two fire history studies that have been conducted (Hawkes 1983 and Francis 1996) suggest that most of the present Kluane stands originated after forest fires. Furthermore, all of the stands that we quickly inventoried or sampled in detail exhibited numerous signs of forest fires.

On the Kenai Peninsula there is no correlation between spruce bark beetle outbreaks and the frequency of forest fires; none of the 20 mature spruce stands examined to date originated as post-fire stands and only one stand shows any evidence of fire (at Funny River Road undated charred wood was found, suggesting a local fire, such as we found at Papineau Road and Ten Km). Historically the Kenai has had a climate that is significantly wetter than the average summer climate of the Kluane region (Fig. 17). Recently, however, warmer summers on the Kenai have increased evapotranspiration, and fire risk has increased. The 1996 Crooked Creek fire and the 1998 Hutler Road fire both spread rapidly through recent beetle-killed forests, and have substantially raised concern about fire on the Kenai.

It is appropriate for people who wish to protect their homes and other value-at-risk to take preventative actions to reduce the dangers that forest fires represent. In fire-prone areas, homeowners should clear defensible spaces around buildings, avoid storing combustible fuels next to buildings, and maintain a driveway where vehicles and firefighters can be moved in quickly in the event of a fire. The recent beetle kill in the Kluane region could be used as an opportunity to promote these efforts. Fire-Smart programs are being implemented in a number of Yukon communities, and the communities in Alaska have also developed similar programs under the FireWise rubric. Information and initiatives among these programs should be shared.

The Kluane beetle infestation could also be an opportunity to use prescribed burning to establish effective firebreaks around communities of the region. Such a program has in part been implemented on the Kenai Peninsula, where the fire hazard is probably lower than it is in the Kluane region. If the climate is indeed warming in Alaska and northwestern Canada (Weller et al. 1999 and 2000), forest fire hazards and the frequency of spruce bark beetle outbreaks can be expected to increase. A defensive program against the damage inflicted by forest fires should be one of the initiatives resulting from the recent Kluane spruce bark beetle infestation.

The Recent Spruce Bark Beetle Outbreak in Kluane

Many forest stands in the Kluane region are presently undergoing a light to severe outbreak of spruce bark beetle. Rod Garbutt's annual "red needle" aerial surveys have documented that during the 1990s and into the present decade, spruce bark beetles have killed mature spruce trees over more than 250,000 ha in the Kluane region (Garbutt, pers. comm.). Downing (1957) offers observations that there was a beetle outbreak in the

1930-40s covering an area near the Alaska-British Columbia border, around Dezadeash Lake, and along the Dezadeash River to near Champagne. Sampling during this study found evidence of this later attack near Papineau Road, and Garbutt found evidence of it near Klukshu. These two widespread beetle infestations appear to be a 20th century phenomena in the Kluane region. Based on the four forest stands sampled as part of our study as well as the scattered trees sampled by Rod Garbutt, it appears that prior to the 1990s most of the white spruce forests in the Kluane region have not experienced a major spruce bark beetle outbreak since the 1600s. Furthermore, the early 1600s were part of the Little Ice Age that in the Kluane region extended from the early 1300s until approximately 1820 (Allen 1982). It is unlikely that spruce bark beetles were active in the Kluane region during the Little Ice Age, given the dependence of the beetles on periods of warm summers (see Appendix A). It thus appears that widespread, severe spruce bark beetle attacks are a 20th century phenomena in the Kluane forests.

This *Dendroctonus* species has probably been a relatively minor player of the ecosystem for centuries, as traditional knowledge seems to suggest. However, it takes special conditions to intensify spruce bark beetle activity into one of these widespread, severe outbreaks. Horizontal trees from blow-downs or road construction slash create favorable conditions for beetle reproduction, and produce several fold as many beetles as compared to standing trees. Warm summers also increase beetle activity and reproduction (Hard 1985, 1987).

Safranyik and Shore (In preparation) review laboratory and field evidence that extremes of temperature can be lethal to *Dendroctonus* larvae (see also Frye et al. 1974). Susceptibility to cold temperatures appears to be greatest in early fall or early spring or whenever moderate temperatures are followed by sudden drops of temperature to below –30 C. Garbutt (pers. comm.) has field observations from the Kluane region that severe cold snaps lasting several weeks can increase over-wintering mortality among the adults and larvae of spruce bark beetles. He observed that a prolonged cold period in the Shakwak valley during the winter of 1995-1996 led to his being unable to find many living spruce beetle larvae or adults on trunks or even root collars of white spruce in this area. Survival of larvae was higher in elevated areas, such as Bear Creek Summit and Boutallier Summit, apparently because of temperature inversions and cold air drainage. Survival was also better in the Mush-Bates area, apparently due to moderating coastal influences. However, Garbutt found that the beetle population was so abundant across the Kluane region that the spread of the infestation continued unabated during the summer of 1996.

In the southern Kenai we have had a string of warm summers that started in 1987, and they have continued to the present time (see Figs. 14,16 and Appendix A). In the past we might get a series of warm summers and the beetles might start up, but then we would get a string of cool summers that would knock them back. For example, 1968-70 was a warm period on the Kenai, followed by cool summers in the 1970s. These cool summers greatly reduced spruce bark beetle activity, and beetle activity on the Kenai did not substantially increase again until the late 1980s (Fig. 14).

Spruce bark beetle dynamics on the Kenai Peninsula appear to be significantly different than they are in the Kluane region. Most of the Kenai forests have been exposed to widespread, intense beetle outbreaks several times during the past 300 years (Berg 1998, 1999). The present beetle infestation is yet another occurrence, although it appears to be the most widespread and probably the most intense, as best we can interpret from the tree-ring evidence. There was a widespread spruce bark beetle outbreak on the entire Kenai Peninsula during the 1810s-1820s, on much of the peninsula in the 1910s, on the southern part of the peninsula during the 1870s-1880s, and on the northern part during the 1970's (Fig. 10A: see also Berg and De Volder, 1999; Fastie et al. 2000). In Kluane, however, we found no evidence of periodic regional spruce bark beetle outbreaks such as we see on the Kenai Peninsula. This is a striking difference, and it is probably attributable to the colder and drier climate of the Kluane region.

The two documented infestations in the Kluane region (beginning approximately 1934 and 1994) appear to be 20th century phenomena. These events appear to be linked to the drier, warmer summers and milder winters that became increasing evident as the century progressed. The warm, dry summers and mild winters of the 1990s certainly exacerbated and increased the spread of the bark beetle across the Kluane region. Whether these warm, dry summers and mild winters are the result of global climate change, El Nino, the Pacific Decadal Oscillation or an interaction of these meteorological processes is beyond the scope of this study to determine. Weller et al. (1999, 2000) present evidence that global climate warming is a major occurrence across Alaska and the Yukon Territory.

During future years if the climate of the Kluane region becomes warmer and drier, the white spruce trees of the region may experience two effects: (1) increased moisture stress, and (2) greater mortality from the increased production of spruce bark beetles. A combination of not only more susceptible trees but, more importantly, enhanced beetle populations from warmer summers may lead to increased attack and mortality of smaller size classes of trees, such as has been observed on the Kenai Peninsula during the 1990s. On the other hand, if the future climate of the Kluane region becomes drier but not warmer (through a reduction in precipitation but little increase in summer temperatures), then these conditions might favor the increase of populations of engraver beetles (*Ips perturbatus, I. Borealis* and *Dryocoetes affaber*) instead of an increase in spruce bark beetle populations (R. Garbutt, pers. comm.).

It is important that additional research be carried out, supported by Parks Canada and other agencies, in order to determine to what extent these changing weather patterns are caused by anthropogenic factors, and what the ecological and economic impacts of global climate change will be.

Sample size of the study

The sample size of the Kluane study is admittedly quite small, with four sites examined in one short field season (2001), in comparison to the Kenai study with 23 sites examined over nine field seasons (1994-2002). The reader might quite rightly ask if our conclusions about the differences between the Kluane and Kenai forests can be legitimately drawn on the basis of such an asymmetrical sample. From a scientific point of view, we would obviously like to have examined many more sites in the Kluane area. Nevertheless, as previously noted, we consider the four sites chosen to be quite representative of the Kluane region. Examining more Kluane sites could, for example, delineate the extent of the 1930-40s outbreak and confirm the historical reportage, but we doubt that it would reveal any pre-20th century outbreaks, such as those detected of the on

Kenai over the last 250+ years. It is also unlikely that our conclusions about the slow growth rate of Kluane trees would change by examining more stands. From a management point of view, we would expect that our conclusions would not be significantly changed by the addition of further sites.

Conclusion

This study suggests that widespread, intense spruce bark beetle attacks in the white spruce forests of the Kluane region are a 20th century phenomena, and that these large infestations were extremely rare in Kluane forests from before 1300 to the 1930s. The 20th century outbreaks appear to be strongly correlated with extended runs of warm summers, most recently in the 1989-1995 period.

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Appendix A: Climate, Bark Beetle Outbreaks, and Tree Growth in the Kluane Area

By Ed Berg

Bark beetle outbreaks and warm summers: Figure 13 shows summer and annual temperatures, as well as the drought index, for Haines Junction since 1945. The red needle hectare data collected by the Canadian Forest Service since 1994 are shown in the lower graph. Fig. 14 presents similar data for the Kenai Peninsula. The annual temperatures for both Haines Junction and the Kenai show the step upward in 1976-77 that Mantua et al. (1997) described as the shift of the Pacific Decadal Oscillation into its positive phase of warm North Pacific sea surface temperatures.

For the purposes of spruce bark beetles, however, the runs of warm summers appear to be the driving force of the beetle outbreaks (see Figs. 13 and 14). The southern Kenai experienced an unbroken run of warm summers in 1987-1997 and the Kluane region experienced a similar but shorter run in 1989-1995. Both areas showed noticeable increases in red needle acreage three years after the onset of warm summers, with red needle acreages accelerating rapidly five years after the onset of warm summers (1992 for the Kenai, and 1994 for the Yukon).

It is instructive to exam the short-lived beetle outbreak that occurred on the Kenai in the early 1970's. This outbreak followed the warm and dry period of 1967-69, which climaxed with the 1969 Kenai burn of approximately 70 000 acres. This fire consumed most of the organic layer and left few unburned inclusions. Large areas of mineral soil were exposed, which led to profuse birch regeneration and a rise in the moose population. A large spruce bark beetle outbreak got underway in the central and northern Kenai, but summer temperatures plummeted in 1971 and by 1974 the outbreak was shut down.

The Kluane area probably experienced a similar short-term bark beetle outbreak in the late 1930's, as shown by the Papineau Road stand and possibly by the Klukshu, Congdon and Dezadeash stands. Fig 10A suggests that Airport Road, and perhaps Ten Km, also displayed slight increases in growth rates during that time. Szeicz and MacDonald (1995) used tree rings to reconstruct June-July temperatures in the Yukon and NWT back to the 1640s. Their reconstructed temperatures indicate a generally warming trend from the 1910s, with an especially warm period in the 1931-38 period, followed by a three-year cooling in 1939-41. This reconstruction, however, does not faithfully track the more recent Haines Junction instrumental record, so it should be interpreted with caution. However, it does suggest that the localized Kluane area outbreak of the 1930s may have been associated with a run of warm summers, as was the pattern during the 1990s outbreak.

There are at least two reasons why a run of warm summers could promote a spruce bark beetle outbreak. First, warmer summers should promote greater beetle production, both through enhanced survival of larvae, and fall pupation of individuals that would normally overwinter as larvae. This early pupation converts normal two-year beetles into one-year beetles. When summers are warm enough for a substantial proportion of beetle larvae to pupate in the fall, a double dose of beetles (one- and two-year beetles) is released in the following spring. This appears to have happened on the Kenai after the long warm summers of 1993 and 1997. When more warm summers are added, the beetle population can grow exponentially, and hence the critical importance of the *duration* of the run of warm summers.

A second effect of warm summers is the possibility of drought stress in the trees. This is a more difficult hypothesis to test, especially without direct measurements of the hydration status of many trees over at least an annual cycle. An argument is made below from monthly climate correlations with observed ring-width growth to suggest that the Kluane trees experience chronic drought stress for at least two periods of the year, and that this stress might explain the slow growth rate of trees in the Kluane area. The Kenai forests, however, do not show any substantial suggestion of drought stress in the climate correlations, and it is more difficult to invoke drought stress as an explanation for bark beetle outbreaks on the Kenai, especially given the cyclic nature of the Kenai outbreaks.

Tree growth and weather: Accurate measurement of tree-rings in many trees provides an opportunity to assess how the local climate affects tree diameter growth in a stand over a scale of decades. It is generally the case that trees in a given area have "sensitive" seasons or months where the weather causes either increased or reduced tree growth, during the present or next growing season (Fritts 1976). For example, Fig. 18 shows that in the Kluane region tree growth is strongly and positively affected by precipitation of the previous September, probably because the soil is able to hold this water in the frozen state over the winter, and thus offset drought stress in the spring. Similarly, tree growth is strongly affected by a warm June, and to a lesser extent by a warm May. To understand these patterns we must examine Figs. 18 and 19 in detail.

To construct Figs. 18 and 19, we first prepared standard chronologies of the tree-ring widths for each site. A standard chronology represents a year-by-year average of the measured ring-widths, where the measurements for each tree have been detrended to remove the effect of exaggerated early growth. This growth trend must be removed from the data, if one wants to see the effect of climate rather than biology. Trees often grow rapidly when young, especially if open-grown as in post-fire recruitment, and their ring-widths decline exponentially with age, as tree diameter increases. We used program ARSTAN (Cook and Holmes 1986) to detrend the data and compute the ring-width indices of the standard chronology for each site. Next, we correlated the yearly ring-width indices with monthly temperature and precipitation values for 16-month periods, running from the previous May to the present August, using program PRECON (Fritts 1996).

In this kind of analysis the obtained climate-ring-width correlations are typically rather low and unimpressive, especially compared, say, to more singular causative effects such as the addition of fertilizer or pesticides. Tree growth responds to many factors, both biological and climatic, but because tree-rings provide large datasets it is possible to statistically tease out weak climatic effects from the biological effects, and correlations that are numerically small become statistically significant because of the large sample size. If, for example, we have a 55-year monthly meteorological record and 55 ring-width measurements, we have 55 paired values of, say, the effect of June temperature on annual ring-widths. For 55 paired values a correlation becomes statistically significant at the 95% level ($p < 0.05$) if it exceeds +/- 0.26 (out of a possible +1.0 or –1.0). Moreover, even if a correlation is not quite statistically significant, we can often see "correlative patterns" where groups of stands are consistently positive or negative in a given month.

Such correlative patterns can be seen in Figs. 18 and 19 between weather (temperature or precipitation) during particular months and the average width of tree rings produced during the growing season.

The strongest climate effects in this type of analysis are normally seen at treeline, because treeline trees are growing at the limit of their climatic tolerances (Fritts 1976). Typically in northern regions the trees at treeline are well hydrated because of heavy winter snowfall, which persists into the growing season, but the trees are stressed for heat or temperature. They will put on a wide ring in a warm summer and a narrow ring in a cold summer. A graph such as Fig. 18 or 19 for treeline would thus show strong positive May-June or June-July temperature correlation peaks, and probably similar peaks for the previous summer (due to the carryover affect of an increased needle crop in a warm year). The graph, however, would typically not show any significant correlations for precipitation, because the trees at treeline usually have enough water.

In the present study, the four Kluane sites and the five Kenai sites are all low elevation sites that are not obviously stressed for either temperature or moisture. Nevertheless, Figs. 18 and 19 show striking differences between the Kluane and Kenai areas that reflect regional climatic differences. Most noticeably, all of the Kenai sites appear to be somewhat stressed for temperature; warm winters and springs all contribute favorably to ring-width growth. There is no consistent pattern of precipitation response, although the two southernmost sites (East Road and Homer) usually respond positively to precipitation at anytime of the year, which suggests slight drought stress at these sites. Overall, the Kenai sites represent a generally moist near-maritime climate, with the two southern sites slightly less well hydrated.

The Kluane sites, by contrast, represent a drier, more continental climate. Warm late winters and springs (Jan-Apr) have a negative effect on tree growth. A plausible explanation for this depressing effect (humans would regard these conditions as nice weather) is that the trees become drought-stressed as they transpire water on warm sunny days when the ground is still frozen and water uptake is prevented. Late winter – early spring drought stress is a well-known phenomenon in northern conifers, and drought avoidance been suggested as a reason why larch (*Larix* spp.) drops its needles in the fall (Berg and Chapin 1994).

In the Kluane area we would expect that most wood deposition (i.e., ring-width growth) typically occurs in June and July. For example, in this study we took our increment core samples in the last week of June 2001, and observed that new growth had not yet started to form a ring in many trees, and had produced only a sliver of growth in others. The month of May was cool that year, being 1.3^{o} C. below the mean, whereas June was 0.7^{o} C. above the mean (Fig. 15, Appendix C). Had May been warmer, ring-width growth would have begun earlier and a wider ring would have been produced over the entire growing season. This is why present May and June temperatures show such a strong correlation with annual ring-width, as shown in Fig. 18.

Somewhat puzzling is the negative effect that *past* summer warmth has on current year growth. Unlike the Kenai, past summer (pJun-pAug) warmth appears to have a retarding effect on ring-width growth in Kluane. This negative effect is especially strong at the Papineau Road site, which also exhibited the most consistent early spring negative temperature effects, as discussed above. Papineau Road was by far the steepest and best-drained site, with slopes up to 26^{o} on much of the site. One possible explanation for the negative effect of past summer temperature is that the trees could become drought-stressed when a warm spring progresses into a warm summer during the previous year. The effect of moisture stress on the trees appears to be carried over into the present year. This interpretation is supported by the generally positive effect of past summer and fall (pJul-pNov) precipitation, because increased precipitation at that time would offset losses due to heat-induced respiration and transpiration incurred during the past summer. Conversely, lack of precipitation in the past summer and fall is correlated with reduced growth in the present year.

As we noted previously, the Kluane white spruce trees generally grow more slowly than Kenai white spruce (Fig. 12). The climate correlations discussed above suggest that chronic drought stress is a possible cause of this reduced growth. The temperature-growth correlations in Fig. 18 suggest that there are two sensitive periods for drought stress: the January to April period of the present year when sunny days can promote photosynthesis and transpirational loss of water, without water uptake from the frozen soil, and the July-August period when the present year growth has been mostly completed but a soil water deficit is accumulated which can carry over to the next spring, unless it is relieved by a wet fall.

It is instructive to contrast the effect of water delivered to the soil in the fall before freeze-up with that of water produced by snowmelt in the spring. As noted, the "wet fall" effect on tree growth in Kluane is substantial, especially with the past September precipitation correlation. The winter snow effect, however, appears to be small. The December though March period contributes about 40% of the total annual precipitation, but only March (which gets by far the least snowfall) has a consistently positive effect at all four sites (Fig. 18). This suggests that much of this 40% of annual precipitation is lost as spring runoff and is effectively not available to the trees for uptake. In the Kluane area a wet fall thus appears to have substantially more effect on tree growth than does a winter with heavy snowfalls.

Haines Junction Climate data – Technical Details: Mean monthly temperature and monthly total precipitation records for Haines Junction, Burwash Landing, and Whitehorse were provided by Bill Miller of Environment Canada in Whitehorse, and for Haines Junction by Brian Luckman of the University of Western Ontario. For Haines Junction, it was necessary to pool data taken at two different stations: a manual station was operated in Haines Junction from Nov 1944 to April 1985, with several missing months in 1983-85. This station was replaced with an automatic station in mid-1985, which failed to deliver data, especially precipitation data, intermittently for many months. Meanwhile, the Yukon Territorial Government (YTG) highway garage started taking manual data in October 1985; this record contains 41 missing monthly values from Oct 1985 to Oct 2002. This station only takes temperatures during the weekdays, but has a cumulative rain gauge that retains rainfall over the weekends. The monthly temperature average is thus based on a 20-23 day month rather than a full month, whereas the precipitation record covers the full month. We merged the data from these two sources (see Appendix C), recognizing that there could be small climate differences between the two sites, as well instrument calibration differences, and the possibility of missing some temperature extremes in the post-1985 data. The Miller temperature data set is nearly complete from Nov 1944 thru 1983, with only 3 missing values. The Luckman data covered the period 1945 through 1995, and contained 48 estimated values for missing months, especially for 1984 to 1992. The record since 1993 through Dec 2002, based primarily on the YTG data, is fairly complete.

For this report, we created a composite Haines Junction temperature data set (see Appendix C), taking the Luckman data as primary, through Sept 1985. For Oct 1985 to Dec 2002 we used the YTG data, supplemented with Luckman's estimated missing values through 1995. We estimated three missing values in the period 1996 to Dec 2002.

Missing values for meteorological data can be estimated with the program MET in the Dendrochronology Program Library software. This program starts with the mean monthly value for the missing month at a given station. It then looks at data for other stations (such as Whitehorse or Burwash Landing) and computes departures (differences) for the month in question from each of those station means. Each departure is rescaled by being multiplied by the ratio of the standard deviations of the missing station to the standard deviation of the observed station. This rescaling adjusts for the fact that stations vary in their range of temperatures, perhaps because one station is located on a large water body that buffers temperature variation (such as Burwash Landing), whereas another station experiences more continental extremes (as is the case with Whitehorse). The estimated value calculation is completed by adding the averaged rescaled departures from the contributing stations to the monthly mean of the missing station. The missing values in the Luckman data set appear to have been estimated with this procedure, and we followed it as well for the three missing values in the post-1995 record, using Whitehorse temperatures. It was necessary to estimate 51 values (or 7.2%) for the 58-year temperature record.

We would also note that generally the Luckman data values agree with the Miller values, but only to within a degree. It appears that one or both of these data sets have undergone some kind of further statistical adjustment, beyond estimation of missing values. The differences are small, however, and are not significant for the purposes of this report.

We prepared a similar composite data set for Haines Junction precipitation. In this case we started with the Miller data set as primary, and used program MET with Burwash Landing precipitation data (Oct 1966 to Feb 1995) to estimate missing values. Missing months not covered by Burwash Landing data were estimated by using Haines Junction monthly means (as calculated from the available raw monthly values, without any estimated values). It was necessary to estimate 58 values (or 8.2%) for the almost 59-year precipitation record.

The climate data for Haines Junction for 1944 through 2002, with estimated missing values, are presented in Appendix C.

Drought Index: We calculated a simple drought index that emphasizes temperature during the summer months (which affects evapotranspiration and plant moisture status) and total precipitation over the hydrological year from October through September. To prepare this index, one first standardizes (normalizes) the mean May – August temperatures by subtracting the average value for all the years available from each yearly value and then dividing these differences by the standard deviation. One next standardizes the yearly October – September total precipitation values in the same way. The standardized precipitation values are then subtracted from the standardized mean

May – August temperatures. The resulting index has a high positive value when the summer is warm and dry, and there was little precipitation over the previous winter. This is a condition that would produce drought stress in plants. Conversely, a cool summer with high precipitation continuing from the previous fall would generate a large negative value for this index. One disadvantage of this index is that extreme precipitation events can produce a large negative value for the year. For example, Haines Junction had a heavy snowfall in January 2000 with 92.5 mm of water equivalent precipitation. This was 3.1x the normal value (Fig. 13). Heavy spring runoff could shunt off most of this water before it could be utilized by plants. So, from the point of view of plants the year 2000 might not have been as moist as the extreme drought index value of -4.5 would suggest. The drought index was developed by Glenn Juday at the University of Alaska – Fairbanks.

Appendix B: Summary of Kluane Burn Dates and Bark Beetle Outbreak Dates

By Ed Berg

Methods: We cross-dated all increment cores and cross-sections (cookies) from dead trees with program COFECHA, using three different parameter settings. In the first setting each tree series was analyzed in 30-year segments, with a 15-year overlap, using a 16-year spline. Each 30-year segment was independently correlated with the same 30-year period of the master dating chronology, which is a filtered yearly average of all the tree ring-widths in the stand. For example, a 105-year series would have six overlapping 30-year periods and hence six tests of its correlation with the master dating chronology. The second parameter setting used 50-year segments, with a 25-year overlap, and a 32-year spline. The third parameter setting used a first-difference transformation of the data, with 30-year segments and 15-year overlap. All three settings gave essentially the same cross-dating results, indicating that all series were consistently dated. We visually compared graphs of individual tree series with the master dating chronology using ITRVIEW software as a further check on the COFECHA dating.

Terminology: In an increment core the *first-ring date* is the date of the oldest complete ring in the core. If the core hit the pith (growth center) of the tree, the pith date would be one year earlier than the date of the first complete ring. Our cores frequently missed the pith by several years, and we made no attempt to estimate pith dates. The *germination date* of a tree is the year that the seed germinated and produced a shoot. We typically cored the trees at waist height (100-120cm), so it is generally necessary to subtract 15-20 years from the first-ring date to estimate the year of germination. To accurately determine the germination date, it is necessary to core at the base of the tree, so as to hit the first year's wood.

The *outermost-ring date* of an increment core or a cookie is the date of the last ring. If the tree was alive when sampled and the wood is intact, then the outermost-ring date should be the year when the tree was sampled (assuming that new wood had begun to form by the time of sampling).

If the tree was dead when sampled, it is necessary to cross-date the measured ring-width series against a dated chronology in order to determine the date of the outermost ring. If the wood is intact, this date is the *death date* of the tree, as might be caused by fire, bark beetles, or other mortality factors. If the outer wood is not intact, say due to sapwood rot or to weathering and erosion of the wood, then the outermost-ring date may predate the actual death date of the tree by an unknown number of years. This error tends to increase with time since tree death, e.g., a weathered and grooved 300-year old burn pole has probably lost more rings than a 60-year old smooth-surfaced beetle-killed tree, with the bark partially intact.

In dating old burns we depend heavily on the use of *burn poles*, which are trees whose branches were burned off, leaving charcoaled nubs, but whose trunks are not charred or excavated by the fire. The lack of charring or excavation of the trunk indicates that the tree was alive when burned, and hence that the date of the outermost ring (if intact) is the date of the fire. We generally do not bother to collect wood that is charred because it may have been dead for an unknown number of years before burning. A death date on such wood could pre-date the actual fire date by decades and be very misleading. It is entirely possible for green wood to be charred in a severe fire, but we know of no way to distinguish charred green wood from charred dead wood, and therefore we usually exclude charred wood.

1. Ten Kilometer Site

This site is located 10 km south of Haines Junction on the Haines Road.

This site contained the oldest trees of all sampled sites, with the oldest tree dating to 1538. We used 68 cores in the chronology, which had an average correlation of 0.567. This chronology was used to cross-date dead wood from all the other sites. In this stand we found evidence of two fires: a stand-initiating fire in the late 1620s, and a localized fire in 1721.

The accelerated early growth of the trees initiating between 1622 and 1675 suggests that this stand initiated after a fire in the late 1620s. Thirty-two of the 68 trees sampled (47%) have first-ring dates between 1622 and 1675; this represents a strong pulse of recruitment (Fig. 3). We sampled only four trees that pre-dated this pulse (with first-ring dates of 1538, 1577, 1599, and 1609); these four trees were presumably residual survivors of an ancestral stand that burned in the late 1620's. Further examination of this site might yield burn poles that could date this original fire more precisely.

We cut 8 cross-sections (cookies) from burn poles in this stand, and their outermost-ring dates ranged from 1715 to 1721. This fire occurred well after the stand was established, as shown by the fact that 30 of the 70 sampled trees had established long prior to the 1721 fire and survived it. The fire was thus either not a stand-replacing fire, or if it was a stand-replacing fire, it burned only part of the stand. Inspection of the ring-width graphs of individual trees (Fig. 2) did not reveal any dramatic growth release after the 1720s. The JOLTS analysis indicated that 3 trees released in 1734-5 (4ARG6261, 11EB6271, 02CG6261) that could conceivably be due to localized canopy thinning by a 1721 fire, although this would be a very delayed response. Many trees showed first-ring dates after the 1730s, which would be consistent with a post-fire pulse of recruitment after 1721.

COOKIE ID	#30yr segments	Avg. Correlation	Ring Date	Quality of Date
05EB6271	5	.54	1716	B
08EB6271	3	.42	1715	C
09EB6271	4	.57	1720	B

12EB6271	2	.68	1719	B-
13EB6271	5	.57	1721	A-
14EB6271	3	.67	1721	B+
15DH6271	5	.57	1721	A-
16EB6271	5	.56	1720	A

These approximately 280-year old poles were well weathered and it is entirely possible that several years of outer rings have been lost by weathering and erosion of the wood. If so, the fire would have occurred a few years more recently than 1721.

2. Papineau Road Site

This site is located 1.6 km south of the junction of Papineau Road with the Haines Road. We chose this site based on the following historical report, as well as Rod Garbutt's personal observation of old beetle-kill in the Papineau Road area.

"An infestation of considerable magnitude occurred along the Haines Cutoff Highway during the 1940's and, although it did not extend into Alaska to any extent, it is worthy of mention. The Alaska spruce beetle, *D. borealis*, caused up to an estimated fifty percent loss of white spruce over an area extending from near the Alaska-British Columbia border on the Haines Cutoff Highway, and following the Upper Dezadeash River, to Mile 974 on the Alaska Highway. This infestation lasted from the early 1940's until 1950. Cause of the outbreak is not known."
(G. L. Downing, December 1957. The Recent History of Destructive Forest Insect Activity in Alaska, *Forest Insect Survey Reports of the Alaska Forest Research Center*, USDA Forest Service, Number 1, pp. 1-4, Juneau, Alaska)

(Note: *Dendroctonus borealis* is now included in *Dendroctonus rufipennis* (Kirby).)

We cored old beetle-scared white spruce boles (both standing and down), and obtained the following distribution of outermost-ring dates (death dates):

Year	Count	Core ID's (Papineau Road core ID's have the suffix 6281 for the date 6/28/01)
1934	2	02EB, 22EB
1935		
1936	3	08EB, 16PR, 23BS
1937		
1938	3	02PR, 08BS, 09PR
1939	2	15CG, 16CG
1940	1	12EB
1941	2	02RG, 19EB
1942	2	07EB, 18PR

After 1942, the next death date was 1997, due to recent beetle-kill. Tree 05DH had an outermost-ring date of 1931, but inspection of the core suggested that an unknown number of outer rings had been lost in the sampling process.

These dates indicate that the infestation had begun by 1934, and probably intensified in the late 1930s and early 1940s. The trees had little or no bark remaining, and it is always possible that the exposed wood has experienced some erosion of the outermost rings. This seems unlikely with wood that is only 60+ years old, however. If wood erosion has occurred, several years should be added to these dates.

We found evidence of two separate fires in this stand. I took cores 18AB and 18BB from a standing snag, which had charcoal nubs but no burning of the trunk. The bole was completely barkless and showed no beetle scars. The outermost-ring dates were 1849 and 1850, respectively. The bole measured 24.4 cm DBH, and was situated on a steep 24^{o} slope, with aspect of 080^{o}. Nearby I took cores 20AB and 20BB from a very similar snag, and both cores had outermost-ring dates of 1850. Slope was 20^{o}, aspect 100^{o}. The two snags were located about as far north as I sampled along the ridge at this site, and were situated roughly three-quarters up the slope.

We have evidence of a much earlier fire from three burn pole cookies that Doug Fisher took on top of the ridge, above and to the south of the two snags which I cored. These were 15DF, 23DF, and 24DF, which had death dates of 1752, 1756, and 1758, respectively. I take 1758 as the best estimate of the burn date, assuming that the earlier dates are due to erosion of several outer rings,

Both of these fires appear to be quite localized, because we only found charcoaled wood in their immediate vicinity. It is possible that the fires represent lightning strikes that did not spread beyond a few trees. It is also possible that they represent tongues or spotting from larger fires outside of the part of the stand, which we sampled. Our sampling of this site was limited to one day, and we did not explore beyond the area that we sampled.

The 1758 and 1850 fires generated 10 and 8 statistically significant releases, respectively, in the next decade. In the ring-width graphic (see Fig. 4), one can see possible releases after the 1758 fire in 18BB and 18AB (duplicates), 16PR, 20BB and 20AB (duplicates), 01PR, and 02PR. Possible releases after the 1850 fire can be seen in 10EB, 06EB, 16CG, 18CG, 25DF, and 13DF.

The Papineau Road stand appears to be an old growth stand. Fig. 5 indicates steady recruitment since the early 1700s. There is no indication of an initial post-fire cohort of trees, such we see at the Ten Km, Marshall Creek, and Airport Road sites. In the fire-rich Kluane area it is likely that every stand initiated after a fire, even if the initial cohort of trees has long since died and rotted away. Digging soil pits in the stand would probably reveal charcoal from one or more burns which pre-date the initiation of the present stand. This charcoal would have to be dated with Carbon-14, using multiple samples to get reliable estimates of earlier burn dates.

3. Marshall Creek Site

The site is located approximately 15 km east of Haines Junction, at 2.2 kms on the Marshall Creek Road.

This was the youngest stand sampled, with many of the trees having first-ring dates in the 1830s and 1840s. The oldest first-ring date was 1796.

Two burn pole cookies were sampled: tree 08DF6261 had 101 rings, with a death date of 1750. Tree 29DF6271 had only 54 rings, with an apparent death date of 1777. This second date is based on a relatively small sample of years, and it should probably be discarded. The first tree correlated well with six 30-yr periods and had an average correlation of 0.59, implying that the 1750 date for the fire is reasonable, although it is based on a single sample.

Figs. 8 and 9 indicate that many trees have first-ring dates in the early 1830s. If we allow, for example, 15 years from germination to the time a seedling is tall enough to be represented in an increment core taken at waist height (100-120 cm), we can estimate that much of this stand initiated around 1815. This is considerably later than the estimated burn date of 1750, and it calls the estimated burn date of 1750 into question.

Three cores were taken from one tree (8AEB6261, 8BEB6261, 8CEB6261) that had grown on top of a piece of old charcoaled wood, which could not be extracted. First ring dates were 1832, 1836, and 1837, respectively, indicating that a fire had occurred an unknown number of years prior to 1832.

Further study of the fire history of this stand should focus on finding more burn poles and coring the oldest possible trees.

Fifty-four dead trees were sampled in this stand. Their death dates (i.e., outermost full ring dates) grouped as follows: prior to 1980 – 3, 1980 – 1, 1991 – 9, 1992 to 1995 – 2, 1996 – 13, 1997 –21, 1998 – 2, 1999 – 4. In the 1990s these dates probably represent the year that the tree was (heavily) infested with bark beetles, with the needles turning red and growth mostly ceasing the following spring. Maximum red needles thus probably appeared in the spring of 1997 and 1998.

4. Airport Road Site

This site is located several kilometers east of Haines Junction on the east side of the road to the Haines Junction Airport.

The abundant old burned and gutted stumps in this stand strongly indicate that the present stand was initiated after a fire. However, we found no dateable burned wood, which suggests that that the fire was severe and that most of the fuels were consumed, leaving only burned stumps. This is a rather dry site on well-drained soils, and the forest could probably burn quite completely during a dry period. Many of the first-ring dates fall in the 1770s and 1780s, suggesting a burn date in the 1750s. We found no evidence, such as burn poles, that any fire occurred since stand initiation. This observation contrasts with Papineau Road (with 1758 and 1850 fires) and Ten Km (with a 1721 fire), which experienced localized fires well after the stands had initiated.

5. Spruce Bark Beetle Interpretive Trail

The site is located on the Alaska Highway north of Haines Junction and south of Boutallier Summit.

Three cores were taken from a standing white spruce burn pole (DBH 26.8cm). No bark remained on the tree, and charcoal nubs from burned off branches were visible. The trunk had not been excavated by fire, indicating that the tree was alive at the time of burning. All three cores cross-dated reasonably well with the chronology from the Ten Km site. The outermost-ring dates were 1885, 1882, and 1873 for cores 01EB6251, 02EB6251, and 03EB6251, respectively. The youngest date (1885) is probably the best estimate of the burn date; the older dates are probably due to loss of outer rings due to erosion of the exposed wood surface. A chronology from a site closer than our Ten Km site might improve the estimates of these dates, perhaps with less scatter of the ages.

Two other cores were taken at this site from recent (unburned) beetle-killed trees. Tree 01CG6251 was a dead white spruce with many beetles scars on the bottom and an outermost-ring date of 1993. A second tree beetle-scarred tree 01RG6251 had an outermost-ring date of 1992.

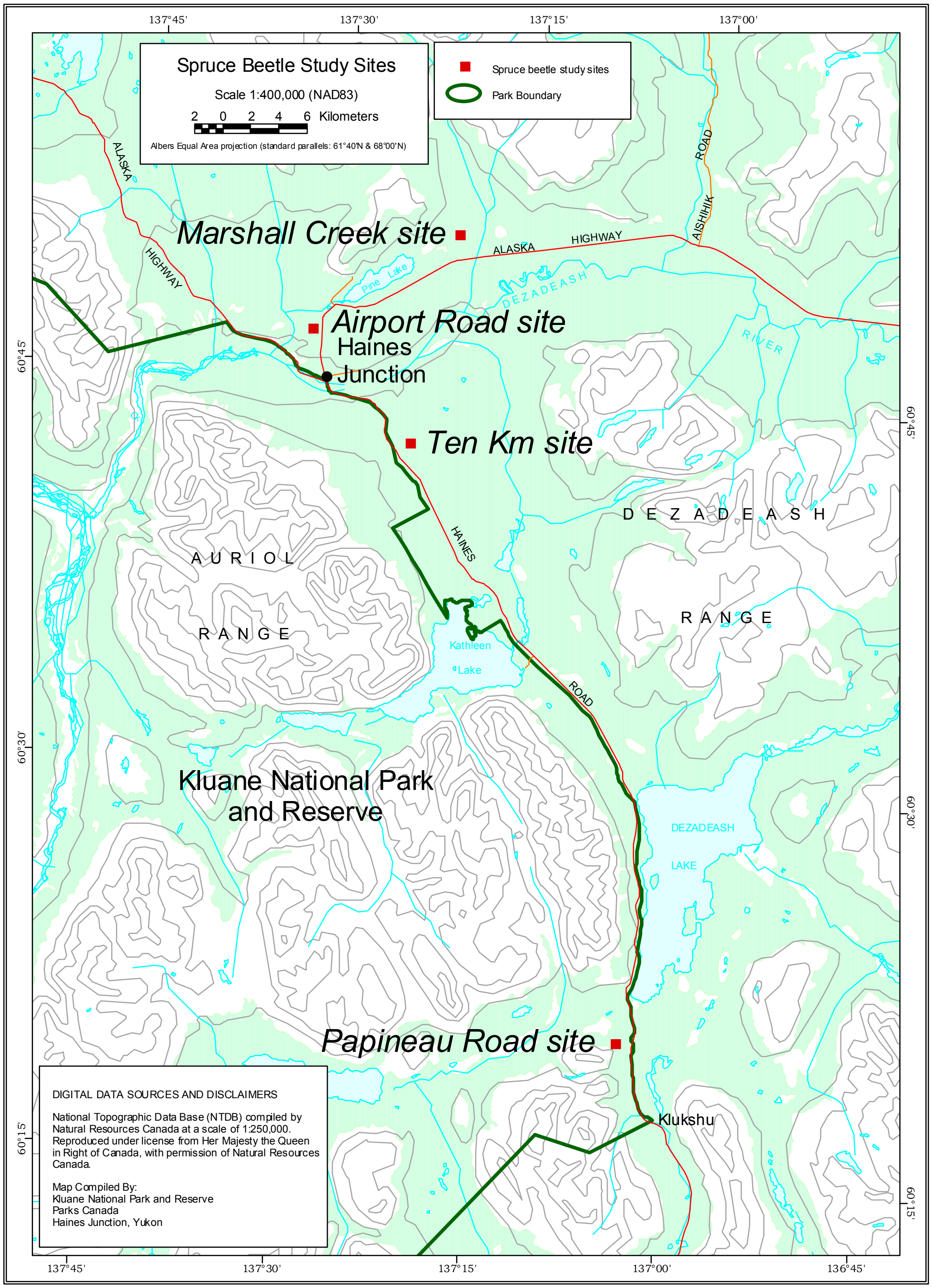
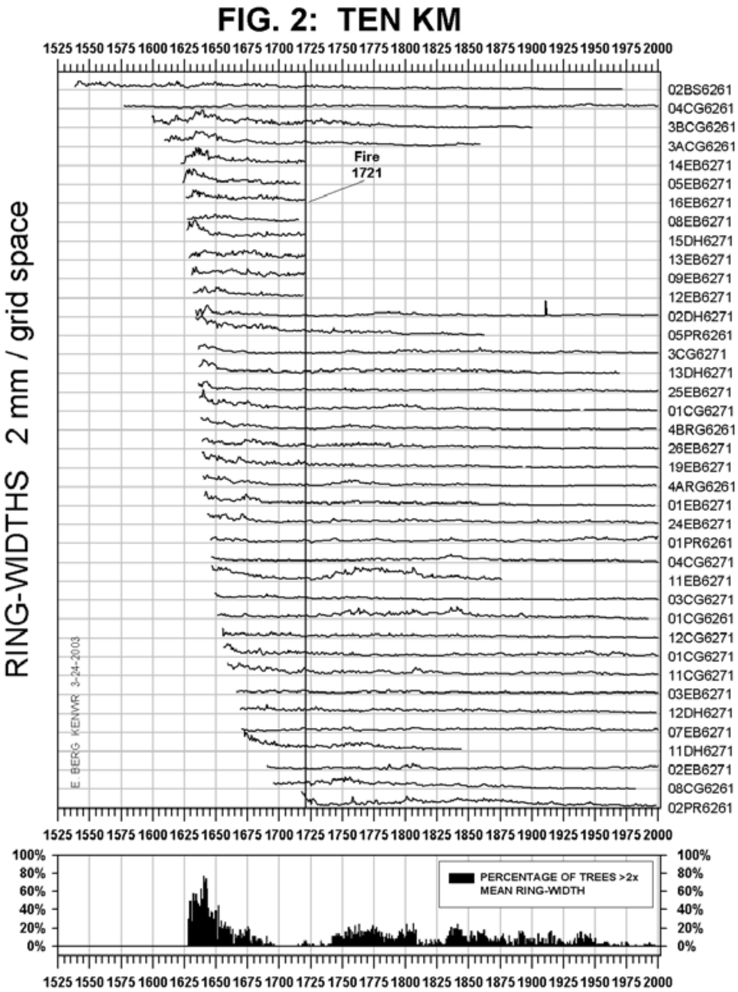


Fig. 1. Map of the four study Sites in the Kluane region.



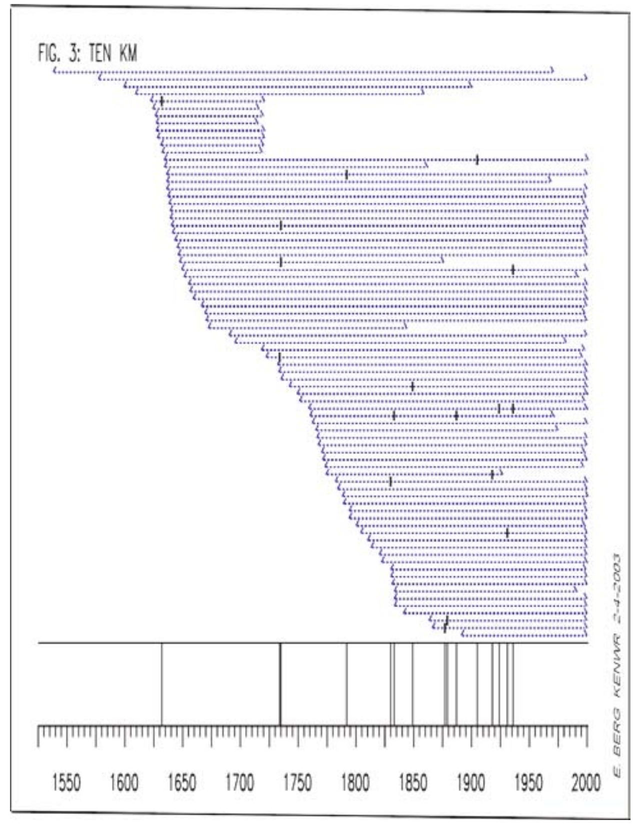
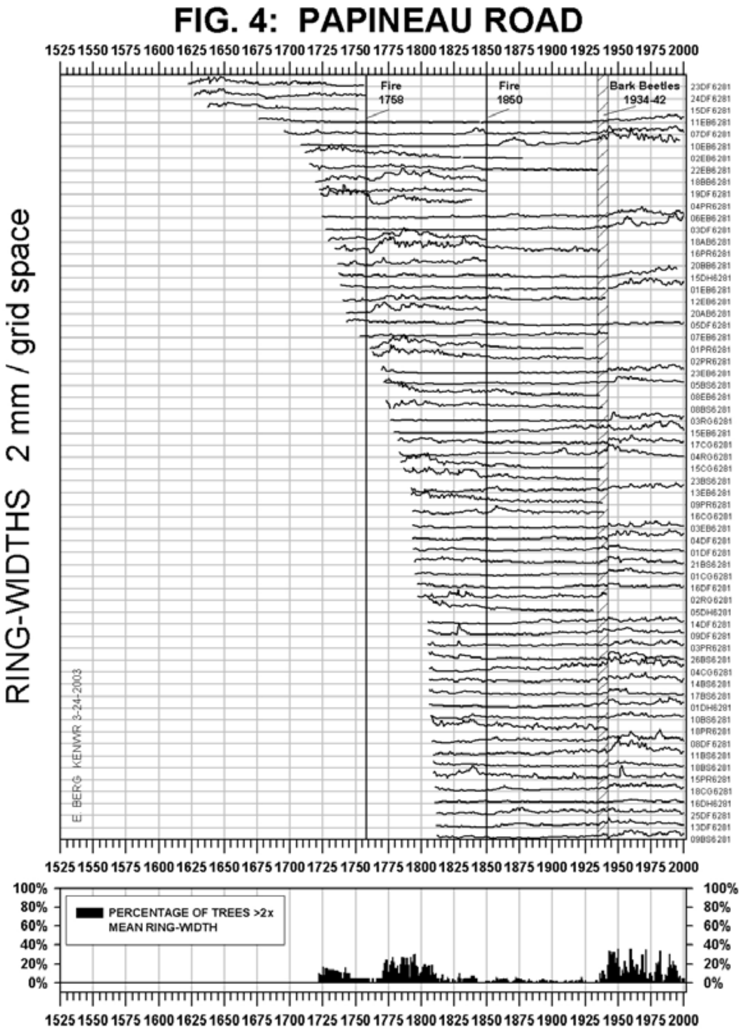


Fig. 2. Ring-width graph – Ten Km site. Measured ring-widths in millimeters are shown for the older trees. Sample ID's appear on the right. The fire date of 1721 is estimated from the outermost ring dates of 8 burn poles. The lower graph shows the percentage of trees growing at more than twice the mean radial growth rate ($n \geq 10$ trees).

Fig. 3. JOLTS graph – Ten Km site. Each horizontal line represents the time span of a single tree, as determined from dated tree-rings. Vertical bars show growth releases. All sampled trees are shown.

Interpretation: Ten Km was the oldest stand sampled. The rapid early growth in the 1600s suggests that this stand initiated after a fire in the 1620s. The rare and scattered releases shown in Fig. 3 indicate that this stand has never experienced a stand-wide thinning event, such as caused by spruce bark beetles. There was no significant release associated with the 1721 fire, according to our definition of a release as doubling of the ten-year mean ring-width. Nevertheless, tree growth accelerates moderately after 1740, possibly due to an opened canopy and fire-released nutrients.



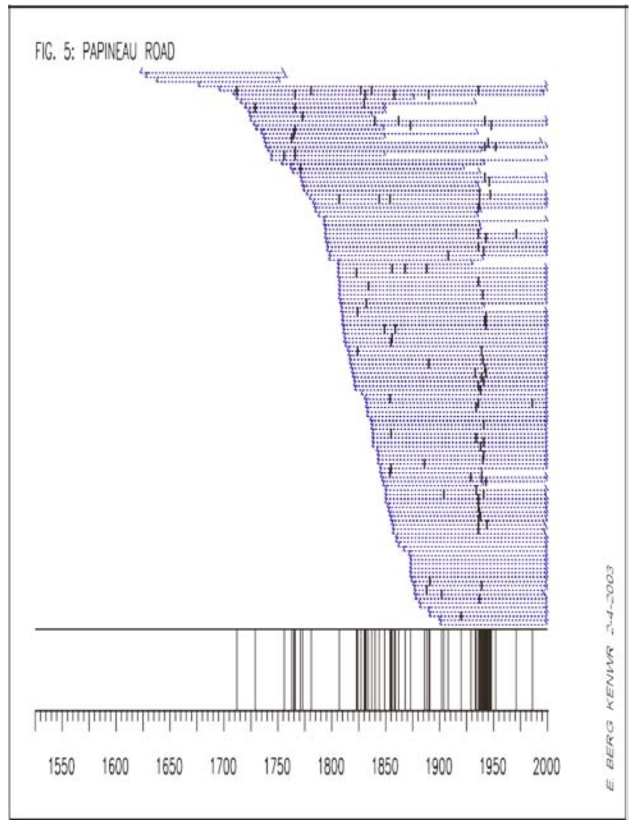
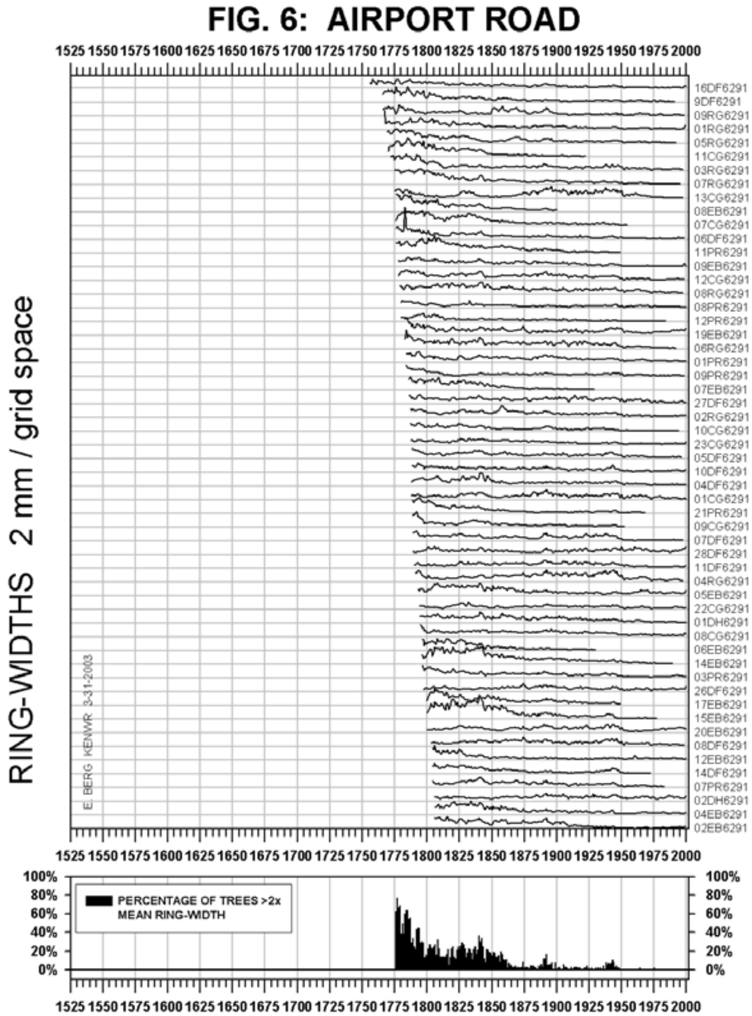


Fig. 4. Ring-width graph – Papineau Road site. Measured ring-widths in millimeters are shown for the older trees. Sample ID’s appear on the right. The fire dates of 1758 and 1850 were estimated from the outermost ring dates of 3 and 5 burn poles, respectively. The bark beetle outbreak dates were determined from the death dates of beetle-scarred trees on the site. The lower graph shows the percentage of trees growing at more than twice the mean radial growth rate (n ≥ 10 trees).

Fig. 5. JOLTS graph – Papineau Road site. Each horizontal line represents the time span of a single tree, as determined from dated tree-rings. Vertical bars show growth releases. All sampled trees are shown.

Interpretation: This stand shows a strong growth release, beginning in the late 1930s and continuing into the late 1990s. The trees terminating in the 1934-42 period have extensive spruce bark beetle scars that clearly indicate that this stand was thinned by beetles during that period. There appears to have been a somewhat delayed growth response following the 1758 fire, although the sample of trees is small during the late 1700s period. No growth response is visible after the 1850 fire, which was probably quite local within the stand.



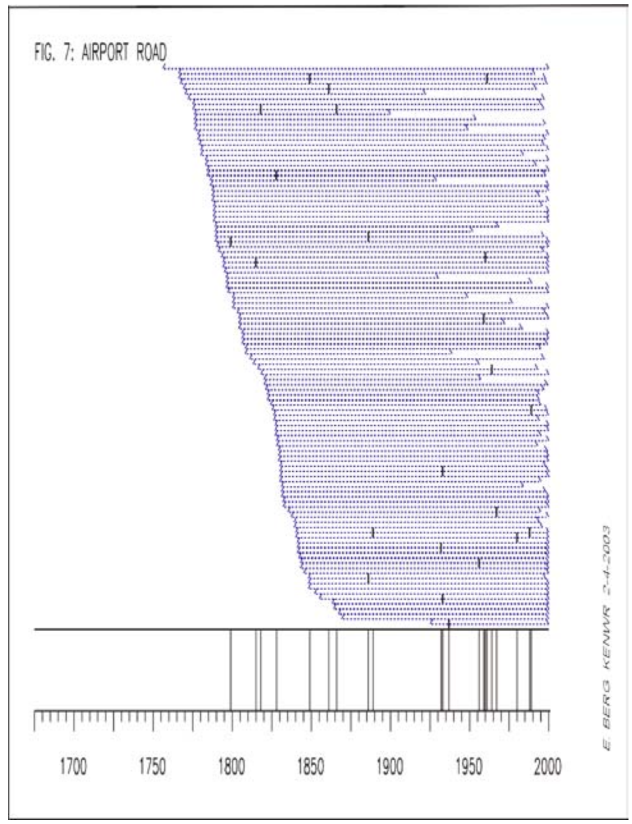
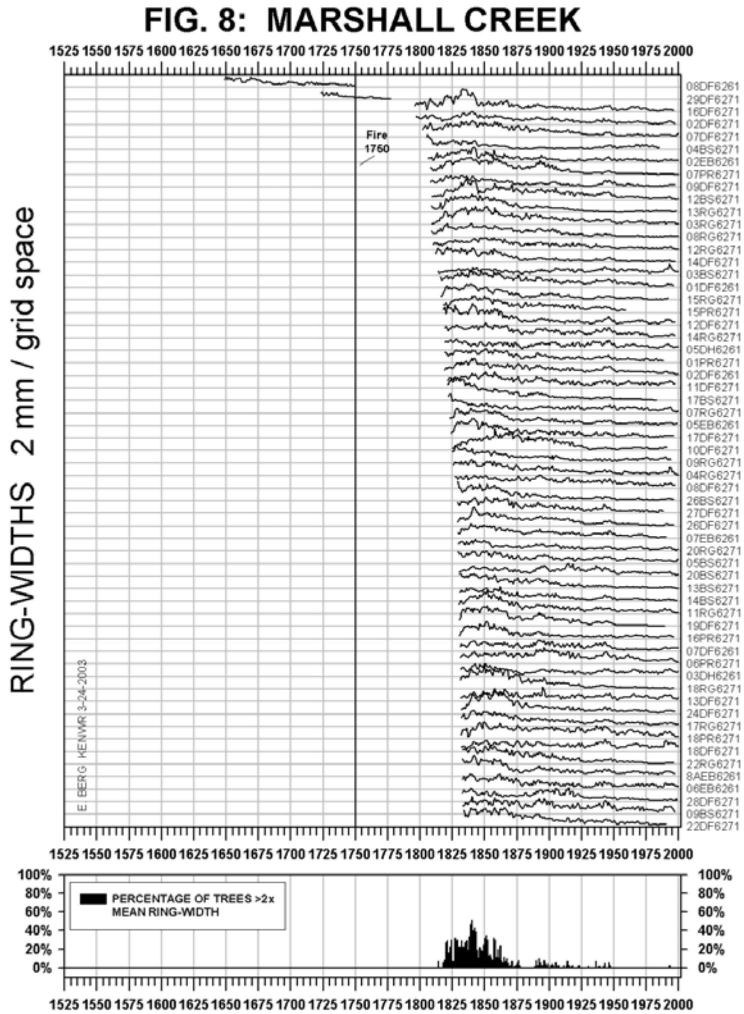


Fig. 6. Ring-width graph – Airport Road site. Measured ring-widths in millimeters are shown for the older trees. Sample ID's appear on the right. The lower graph shows the percentage of trees growing at more than twice the mean radial growth rate (n ≥ 10 trees).

Fig. 7. JOLTS graph – Airport Road site. Each horizontal line represents the time span of a single tree, as determined from dated tree-rings. Vertical bars show growth releases. All sampled trees are shown.

Interpretation: The rapid early growth in the late 1700s suggests that this stand initiated after a fire in the 1750s. The rare and scattered releases shown in Fig. 7 indicate that this stand has never experienced a stand-wide thinning event, such as caused by spruce bark beetles.



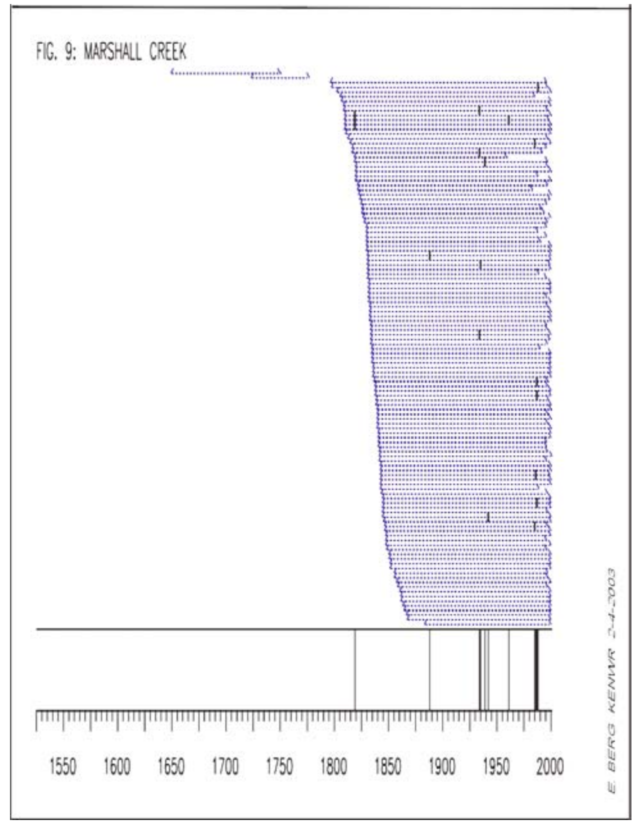


Fig. 8. Ring-width graph – Marshall Creek site. Measured ring-widths in millimeters are shown for the older trees. Sample ID's appear on the right. The fire date of 1750 was estimated from a single burn pole. The lower graph shows the percentage of trees growing at more than twice the mean radial growth rate ($n \geq 10$ trees).

Fig. 9. JOLTS graph – Marshall Creek site. Each horizontal line represents the time span of a single tree, as determined from dated tree-rings. Vertical bars show growth releases. All sampled trees are shown.

Interpretation: This was the youngest stand sampled. The rare and scattered releases shown in Fig. 9 indicate that this stand has never experienced a stand-wide thinning event, such as caused by spruce bark beetles. The rapid early growth suggests post-fire stand initiation. Two samples of burned wood (with death dates of 1750 and 1777?) pre-date stand initiation by as much as several decades. Allowing 10-20 years for the trees to reach waist height, where the trees were cored, would suggest that this stand initiated after a fire in the 1780s, rather than in 1750 which the burned wood indicates. Possible explanations for this timing discrepancy would include inaccurately dated burned wood, more than one burn, and a lack of nearby seed trees after a large, severe fire.

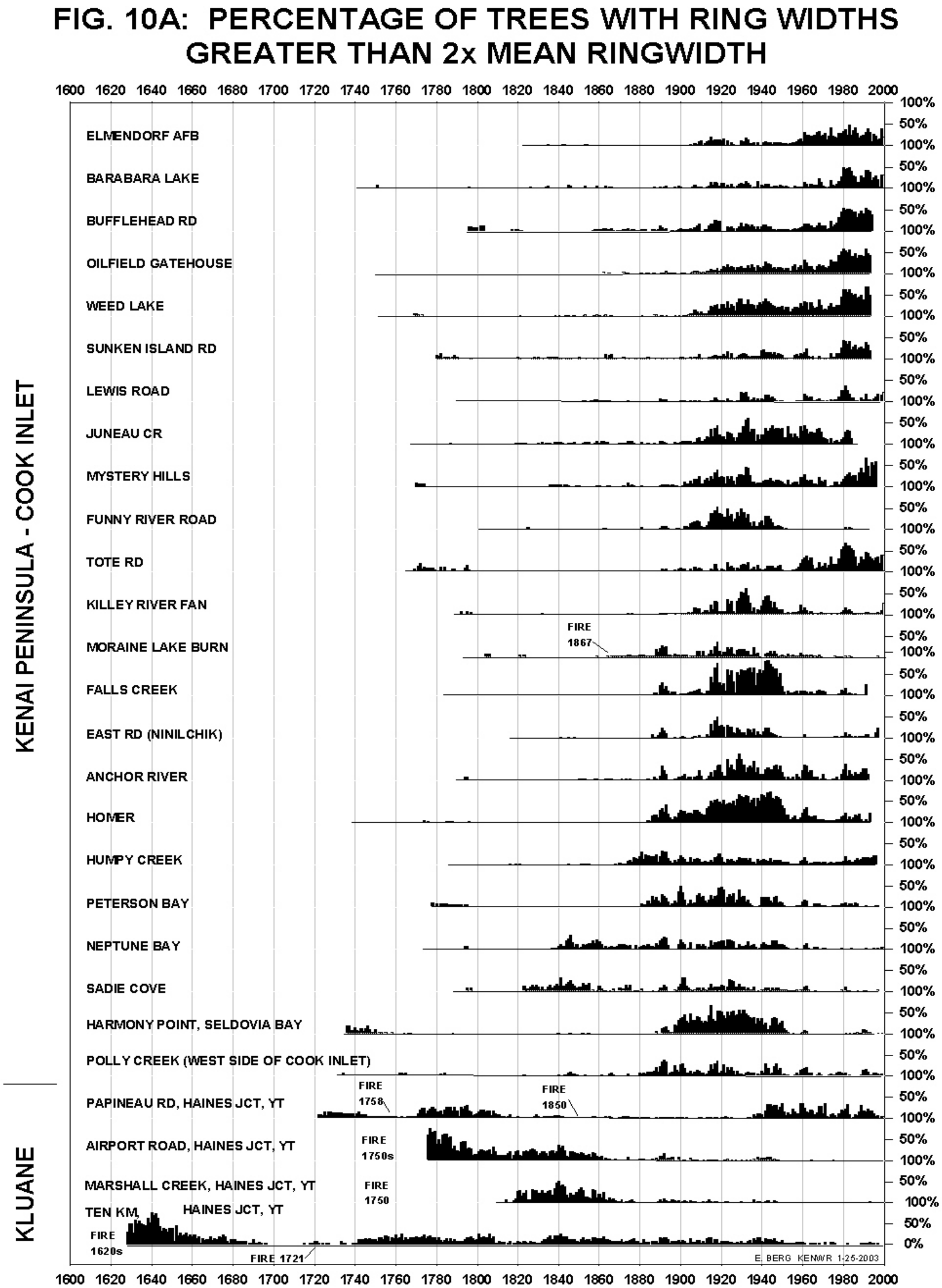


Fig.10A. Percentage of trees with ring-widths > 2x mean ring-width (Kenai and Kluane). Kenai Peninsula stands are arranged from north to south down the page. These stands are mature or old growth white, Lutz, or Sitka spruce, with up to 50% hardwoods.

Fig. 10A Interpretation: All of the Kenai Peninsula – Cook Inlet sites show pulses of accelerated growth releases, usually after many decades of suppressed, slow growth in closed-canopy forests. The growth releases are in response to thinning of the forest canopy, presumably by spruce bark beetles. Strong regional thinning patterns are evident in the 1970s and 1910s in the central and northern Peninsula sites, in the 1870s in the southern Peninsula sites. Small but statistically significant releases can be seen in some sites in the 1810-1820s across the entire western Peninsula.

In the four Kluane stands, only Papineau Road shows a stand-wide growth release (in the 1930-1940s) as a mature stand. Historical records (Downing 1957) document a spruce bark beetle outbreak in the 1940s in this area. The other three Kluane stands experienced rapid early growth, presumably as post-fire stands, but they show no growth releases as mature stands, and hence no evidence of canopy thinning due to spruce bark beetles.

All stands in this graph experienced substantial spruce bark beetle infestation during the mid- to late-1990s (and continuing to the present, in many cases), with mature tree mortality ranging from 50% (Kluane) to 80-100% (Kenai Peninsula – Cook Inlet).

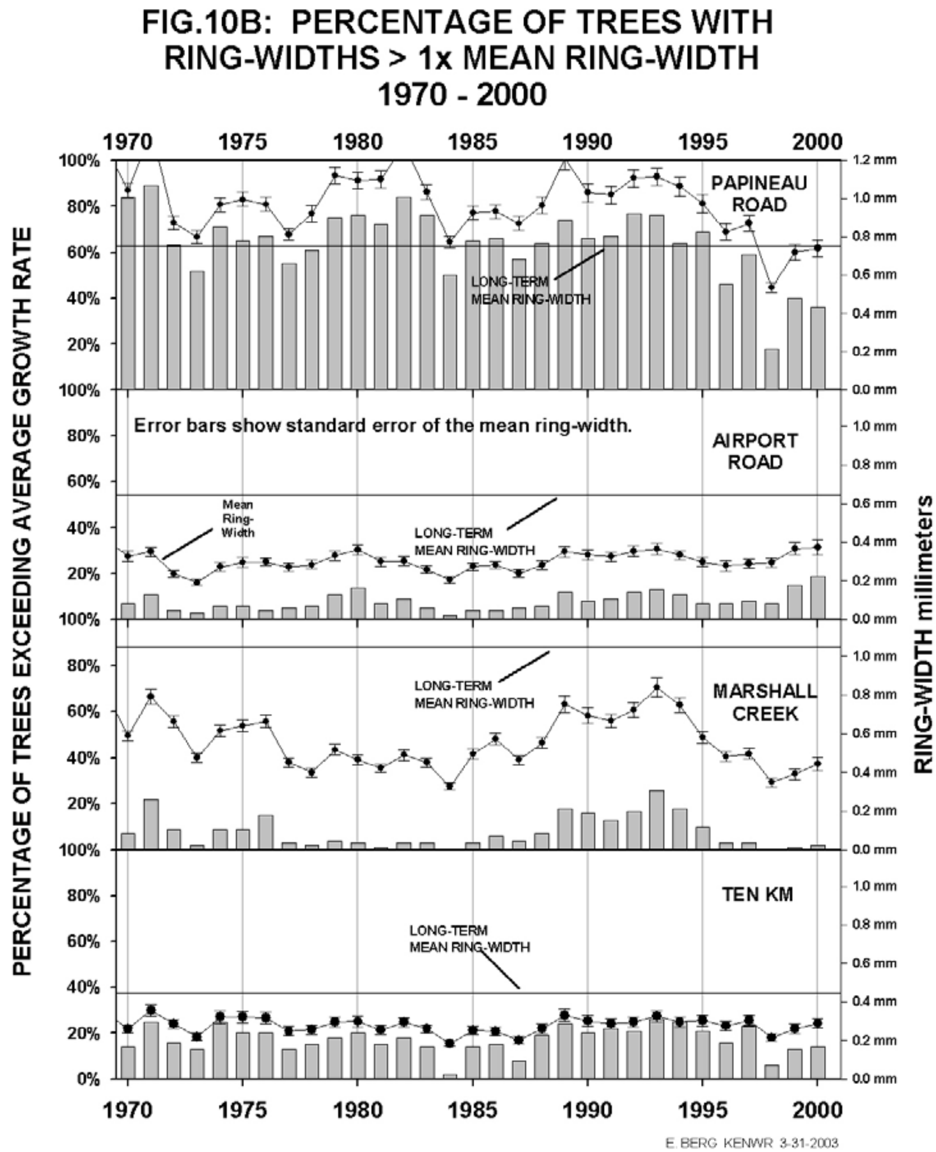


Fig. 10B. Percentage of trees with ring-widths > 1x mean ring-width, Kluane 1970-2000. Gray bars show the percentages, using the left-hand scale. Varying lines shows mean ring-widths with bars of +/-1 standard error, using the right-hand scale.

Interpretation: Only Papineau Road shows a substantial proportion (50-80%) of trees growing faster than the long-term mean of the stand. This rapid growth is a continuation of the release initiated in the 1930s, following substantial spruce bark beetle thinning of the canopy. The release appears to be terminating in the late 1990s, presumably with canopy closure.

Trees in the other three stands are competing under closed canopies. A slight growth increase in 1999 and 2000 is possibly in response to mid-1990s beetle kill of neighboring trees.

FIG. 11: RELEASE PROBABILITIES ALL SPECIES, ALL SITES

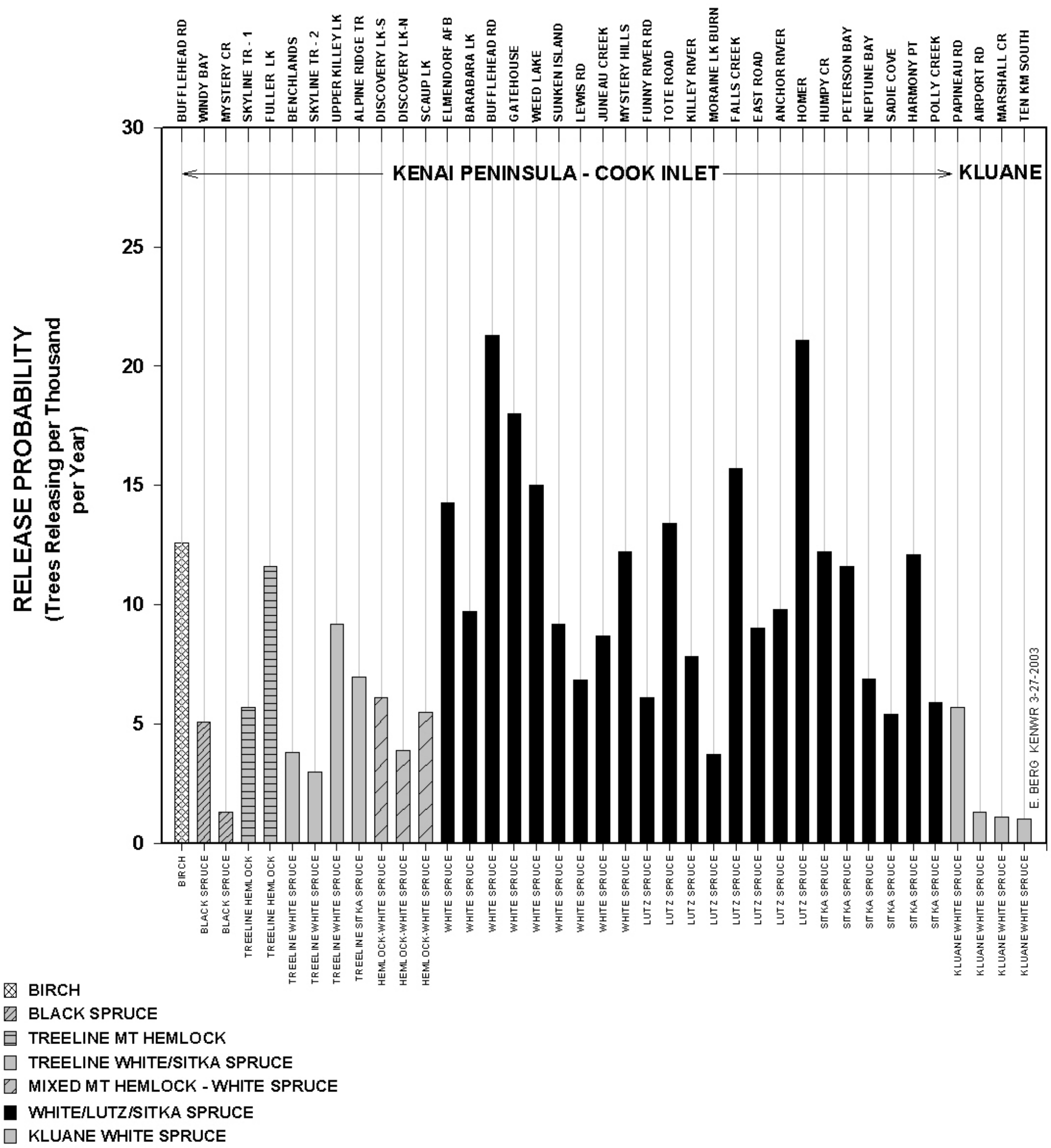


Fig. 11. Release probabilities: all species, all sites, Kluane and Kenai.

Interpretation: We estimated release probabilities with the observed proportion of trees whose tree-rings showed accelerated growth pulses at some point during the life of the tree. Stands with canopy-thinning disturbance exhibit more releases than do undisturbed stands. All lowland Kenai Peninsula – Cook Inlet white/Lutz/Sitka spruce stands (black bars) show high rates of release, as does the Papineau Road stand from Kluane. The rightmost three Kluane stands represent undisturbed stands.

The Benchlands and Skyline Tr-2 stands are open-grown (non-competing) white spruce trees at treeline, which are sensitive to substantial year-to-year variation in summer temperatures. A run of warm summers after a cool period can generate an apparent release in these temperature-stressed trees. The mt. hemlock stands at Skyline Tr-1 and Fuller Lake are also at treeline, and appear to be more temperature-stressed than the treeline white spruce, to judge from their higher rate of apparent release.

FIG. 12: RADIAL GROWTH RATE ALL SPECIES, ALL SITES

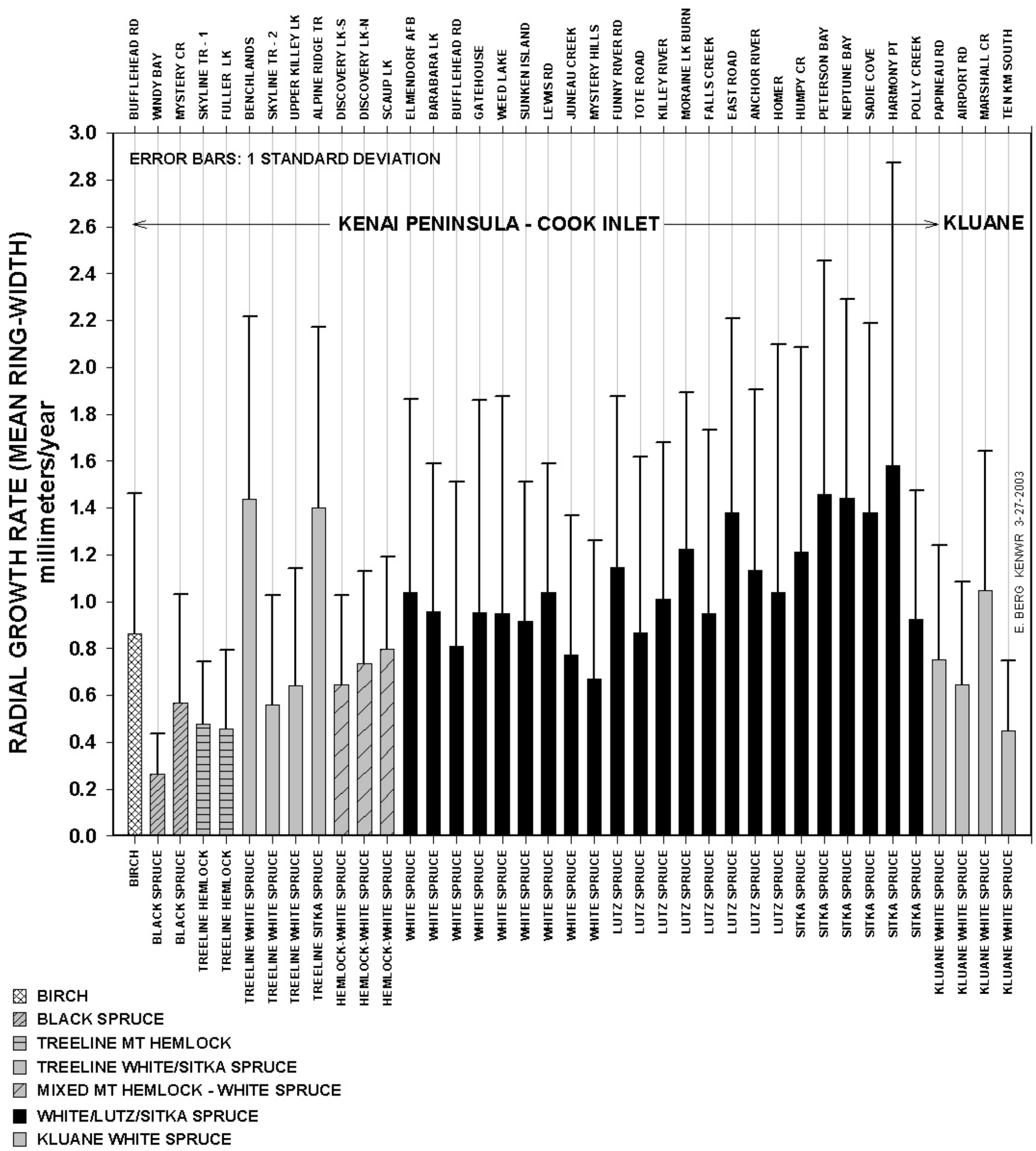
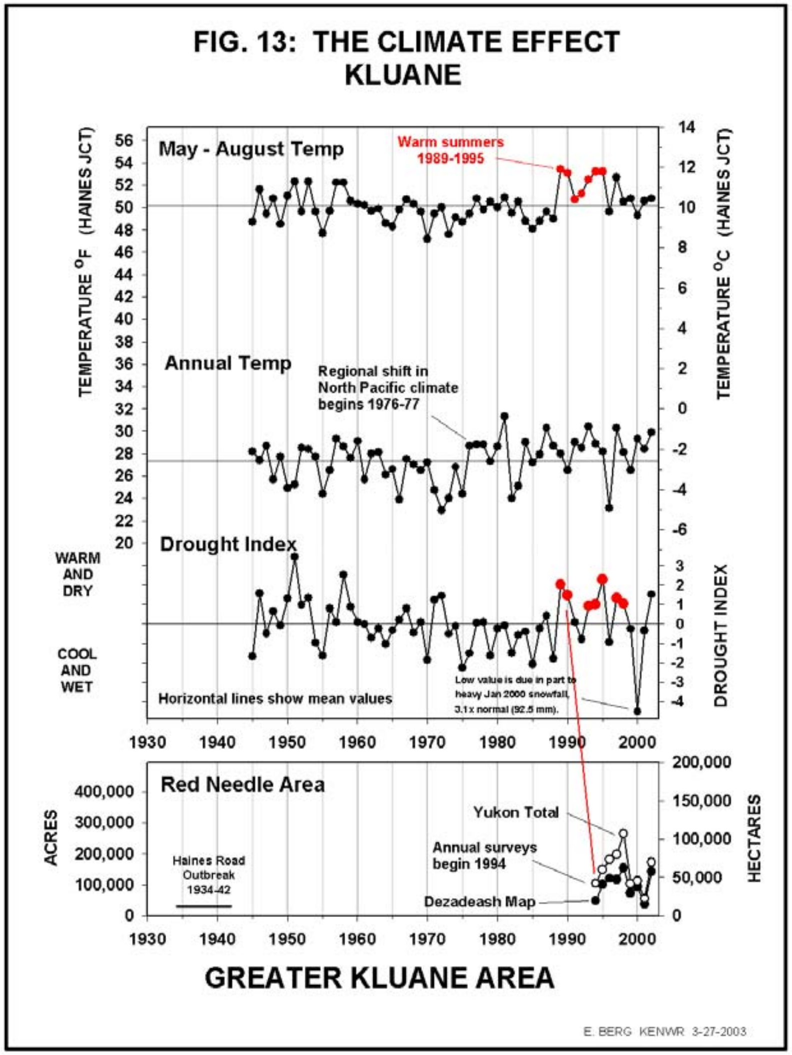


Fig. 12. Radial growth rates: all species, all sites, Kluane and Kenai. Vertical bars show mean ring-width, with error bar of 1 standard deviation.

Interpretation: The Kenai lowland white/Lutz/Sitka spruce stands (black bars) show large within-stand variation (i.e., large standard deviations) in radial growth rate because these were slow-growing mature stands, thinned by bark beetles and subsequently experiencing decades of accelerated growth.

The four Kluane stands are growing substantially slower than most of the Kenai stands, even under conditions of release (Papineau Road) or relatively young age (Marshall Creek, at 200 years).



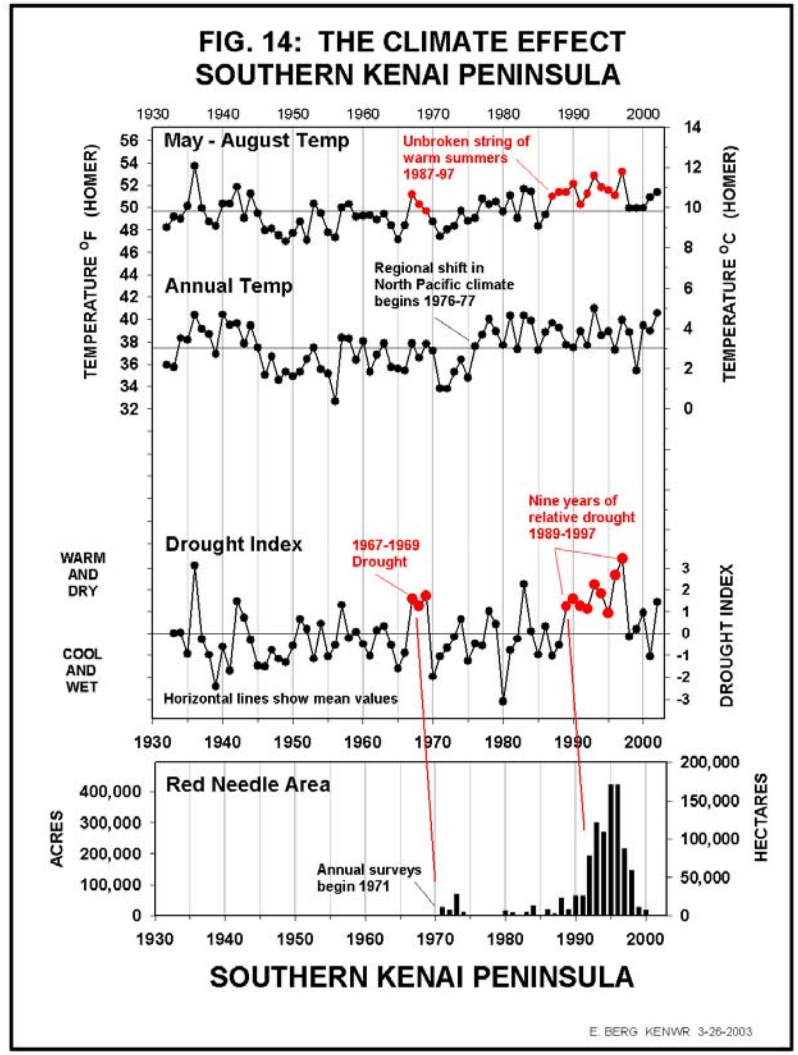


Fig. 13. The climate effect – Kluane area (Haines Junction, YT climate data)

Fig. 14. The climate effect – Southern Kenai Peninsula (Homer, AK climate data)

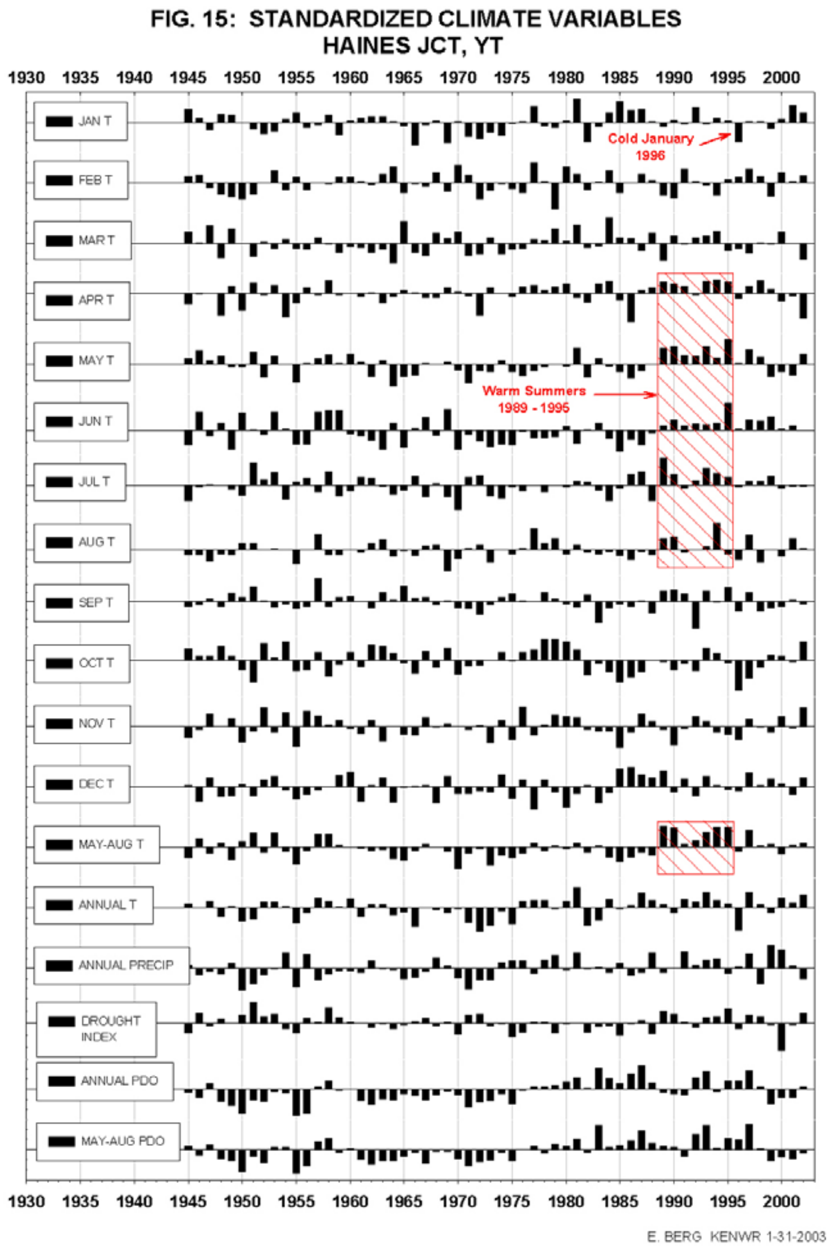
Fig. 13 Interpretation: The run of warm and dry summers of 1989-1995 (and 1997) is unprecedented in the available meteorological record, from 1945. We hypothesize that multi-year runs of warm summers primarily promote better bark beetle brood production, and secondarily cause drought stress, which makes the trees more susceptible to bark beetle infestation.

Summer temperatures since 1998 have hovered close to the mean, but summers were substantially wetter for the 3-year period 1999-2001, especially in 2000. The summer water balance (precipitation minus potential evapotranspiration or P-PET, for May-Aug) is always negative at Haines Junction, because summer evapotranspiration exceeds rainfall, with a long-term mean of –188 mm. The recent P-PET values illustrate the 1999-2001 wet summers: 1998 –259mm, 1999 –161mm, 2000 –84mm, 2001 –157mm, 2002 –193mm. The summer of 1998 was the driest year on record, according to P-PET, and it also showed the peak red-needle acreage. The relatively dry summer of 2002 likewise showed a substantial increase in red-needle acreage, as shown in Fig. 13. The *Yukon 2002 Forest Health Report* (Garbutt 2003) suggests the previous wet summers delayed the final mortality of infested trees, so that red needles didn't appear until the summer of 2002. This would mean that the red-needle acreages of the wet summers were somewhat underestimated, whereas the 2002 acreage represents a catch-up of the underestimated years, and is thus somewhat inflated as an annual mortality rate. Even so, the report emphasizes that the 2002 acreage increase is a real and substantial, and not merely an artifact of the variable weather and survey conditions.

Fig. 14 Interpretation: The run of warm and dry summers of 1987-1997 is unprecedented in the available meteorological record, from 1932. A bark beetle outbreak initiated in the warm and dry period of 1967-1969, but terminated abruptly with the cool and damp period of 1970-1973, of which the summers of 1971-1973 were especially cool and damp. The fact that red needle acreage continued to increase for four years after the summers cooled (until 1973) reflects the lag created by the 2-year life cycle of the beetles and the 1 to 3 years requires for a tree to die, depending on the degree of infestation. The 1973 spike in red-needle acreage may be analogous to the 2002 catch-up spike in the Kluane red-needle acreage. In the Kenai case the subsequent 1974 recovery of warmer and dryer conditions was not sustained, and the outbreak was completely shutdown. In Kluane the summers of 2003 and 2004 should thus be important to watch: if they are cool and damp, the outbreak could be essentially shut down. If the next two summers are warm and dry, the outbreak could be substantially accelerated.

The major sustained outbreak of the 1990s followed the 1987 warming. The decline in red needle mortality after 1996 primarily reflects a decline in available host trees, and perhaps secondarily the somewhat cooler summers since 1998.

In both graphs the increase in annual temperature beginning in 1976 represents a shift to the positive phase of the Pacific Decadal Oscillation (PDO), which is 40-50 year cycle in North Pacific sea surface temperatures. The PDO appears to have turned negative in 1999 but this downturn is, to date, better expressed in summer temperatures than in annual temperatures in the Kenai and Kluane areas. (See PDO graphs in Figs. 15 or 16.)



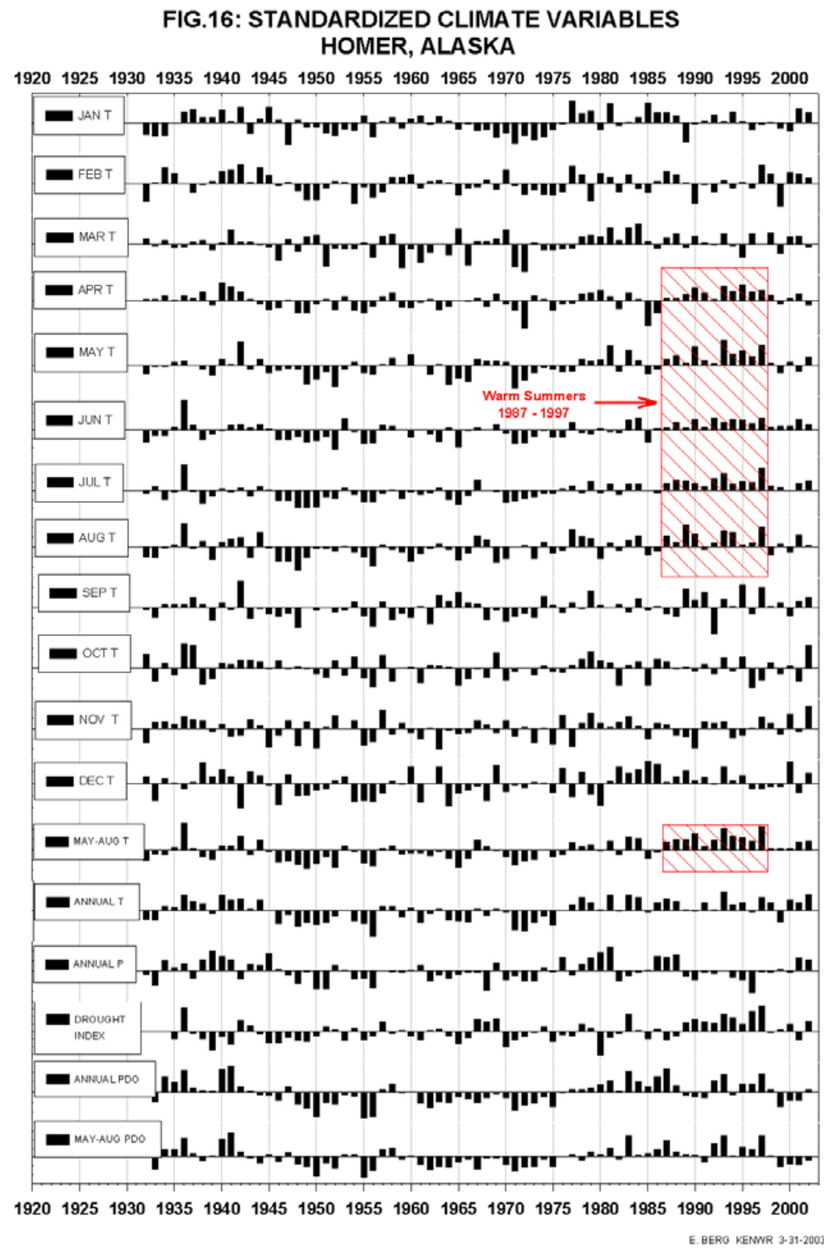


Fig. 15. Standardized monthly climate variables – Haines Junction, YT
Fig. 16. Standardized monthly climate variables - Homer, AK

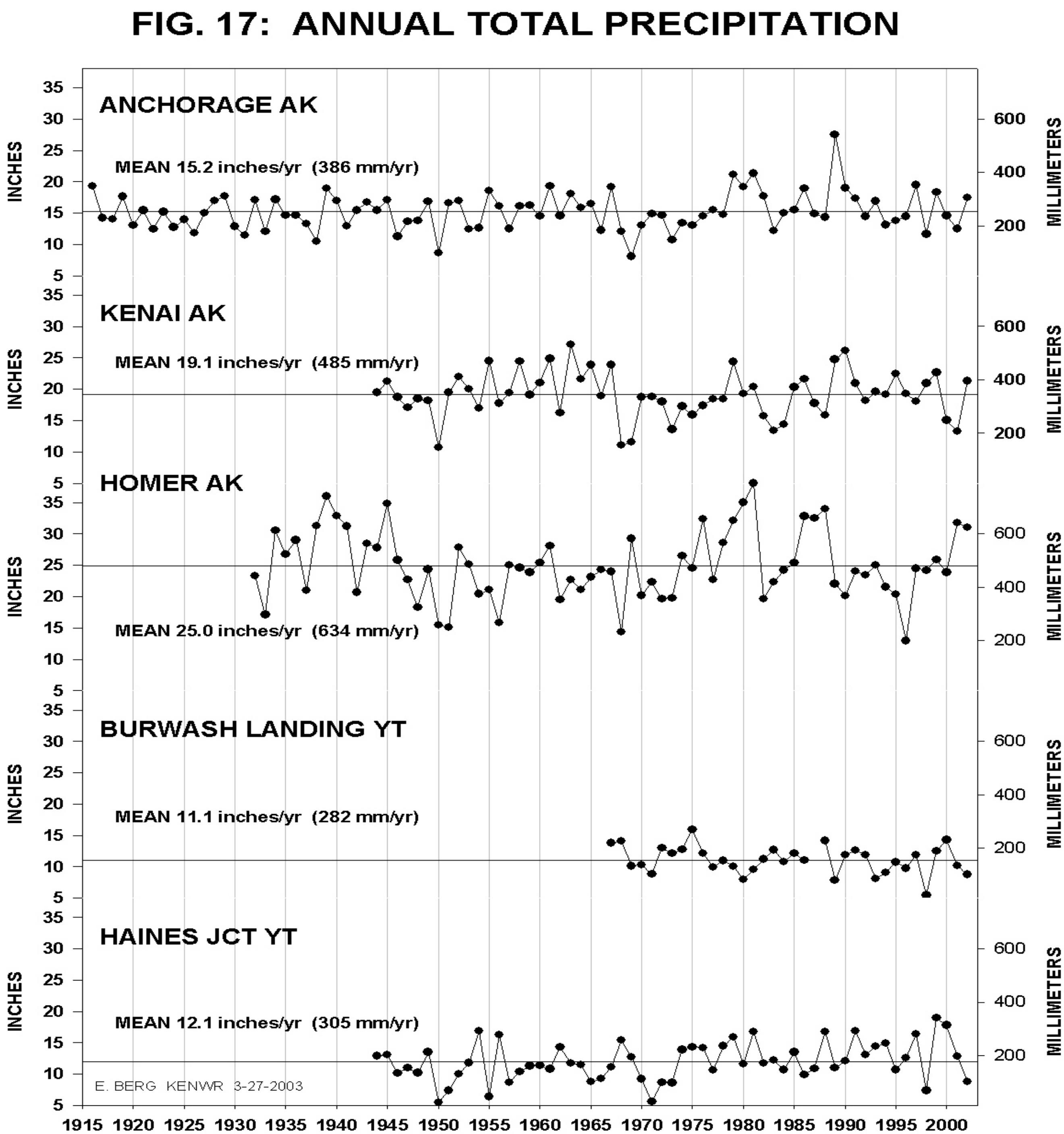


Fig. 17. Annual total precipitation: Anchorage, Kenai, Homer, Haines Junction, and Burwash Landing.

Interpretation: The three Alaska stations are Cook Inlet coastal stations that lie in the rainshadow of the Kenai-Chugach Mountains. The two Yukon stations are continental stations, with substantially less precipitation than the coastal stations. The coastal stations show many runs of 2-4 wet or dry years, suggesting an El Nino – La Nina cycle. The amplitude of variation in the Yukon stations is less than that of the coastal stations, and the cyclic pattern is present but more subdued.

FIG. 18: KLUANE STANDARD CHRONOLOGY TEMPERATURE CORRELATIONS

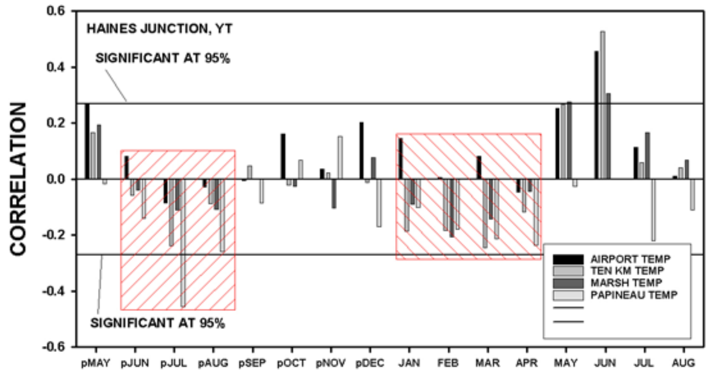
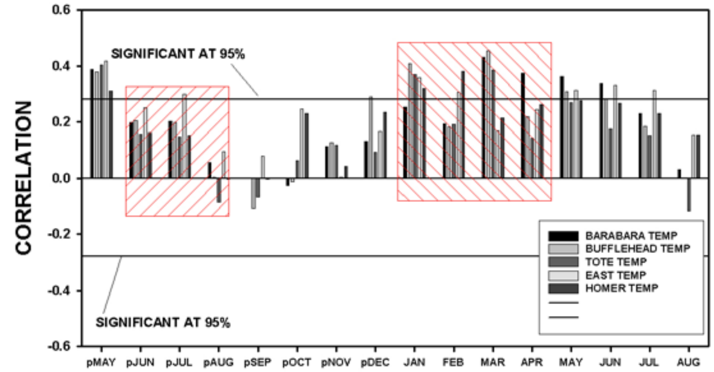
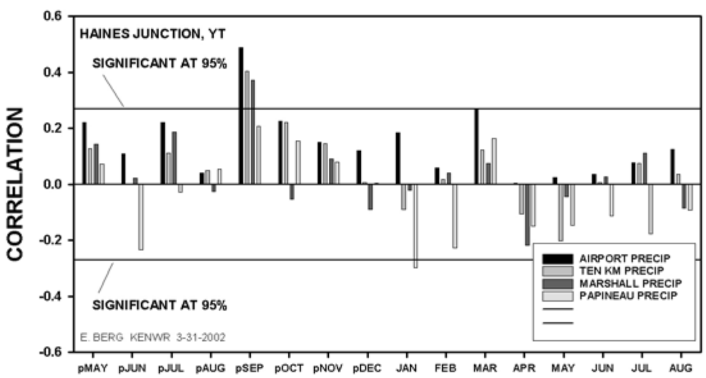


FIG. 19: KENAI STANDARD CHRONOLOGY TEMPERATURE CORRELATIONS



KLUANE STANDARD CHRONOLOGY PRECIPITATION CORRELATIONS



KENAI STANDARD CHRONOLOGY PRECIPITATION CORRELATIONS

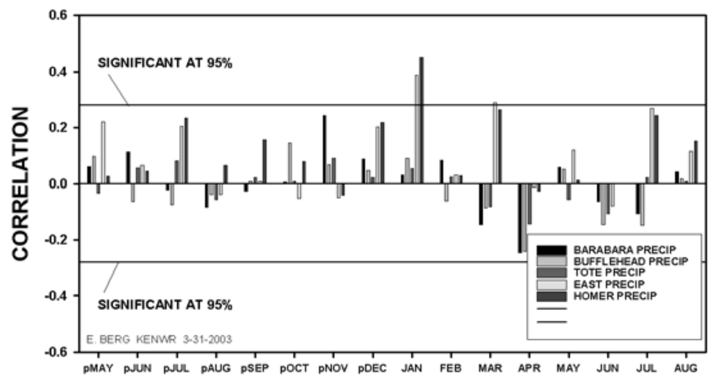


Fig. 18. Kluane standard chronology temperature and precipitation correlations with tree-ring growth.

Fig. 19. Kenai standard chronology temperature and precipitation correlations with tree-ring growth.

Cross-hatched boxes denote periods of contrasting growth response to monthly temperature in the trees of the Kluane area as compared to the Kenai Peninsula.

Interpretation: The Kluane stands have two pronounced periods of sensitivity to weather. The temperatures in May and June strongly affect tree-ring growth during the summer. This is typical of northern forests where the growing season is short. The second sensitive period is in the fall, when the amount of pre-freeze up precipitation has a significant effect on ring-width growth during the following summer. Fall precipitation can be stored in the soil for use during the following spring. Winter precipitation (i.e., snow) is typically lost through spring run off and usually does not show a strong correlation with tree-ring growth.

The Kenai stands show no consistent pattern of moisture response, which suggests that the trees are not drought stressed. Curiously, the Kenai stands appear to be stressed for temperature, because they respond positively to warm temperatures for the first seven months of the year (January through July). This contrasts strongly with the Kluane pattern, where the temperature effect is concentrated in May and June.

Essentially, there are two periods where the temperature response of the Kluane and Kenai trees is quite opposite: past summers (pJUN-pAUG) and “late winter” (JAN-APR). (See cross-hatched boxes in Figs. 18 & 19.) In Kluane, warm weather in both these periods depresses tree growth during the next summer, whereas warm weather in these periods on the Kenai enhances tree growth. This is quite a striking difference, for which we would offer the following hypotheses.

The negative effect of past warm summers in Kluane is possibly due to drought stress of the trees, with increased transpiration and respiration. This hypothesis is supported by the generally positive correlation with precipitation during the past summer and fall, which could counteract the summer drought stress. On the Kenai, however, the higher summer precipitation generally precludes this kind of summer drought stress from developing.

The negative effect of warm late winters in Kluane is possibly also related to drought stress, when bright sunny days promote photosynthesis and transpiration; the stomata of the needles are wide open, and moisture is transpired which cannot be replaced, due to frozen soils. This kind of late winter drought stress probably does not routinely occur on the Kenai because late winters are highly variable, starting with a “January thaw” and followed by various “unseasonably warm” periods (which may or may not be terminated by a cold snap). Depth of freezing in the soil is highly variable, depending primarily on snow cover. On this hypothesis, Kenai trees are able to photosynthesize effectively (i.e., store food for summer growth) in late winter during warm periods, whereas such activity in Kluane trees creates drought stress and reduces subsequent tree-ring growth.

The above hypotheses are based solely on correlation evidence, and there may be equally plausible alternative hypotheses. Further evaluation could be made by examining similar data sets from other climatic zones. See Appendix A for further discussion.